THE UNIVERSITY OF ALBERTA

COAL IN THE MANNVILLE GROUP (L. CRETACEOUS) OF WEST CENTRAL SASKATCHEWAN

by

SYDNEY LEUNG

A THESIS

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ABSTRACT

The Lower Cretaceous Mannville Group in west-central Saskatchewan is wedge-shaped, thickening towards the north. It lies unconformably on Devonian strata in the north and in the south mainly on Mississippian beds which form an east-west trending ridge.

The basal Dina Member of the Mannville is thickest in erosional valleys on the sub-Cretaceous topographic surface and thins over erosional highs. Following deposition of the Dina sandstone, relief on the depositional surface was subdued. The Cummings Member, which has a thin shale unit at the base and becomes sandy towards the top, was deposited by the Clearwater Sea over this surface. The Dina and the Cummings Members do not extend farther south than Township 40.

A coal seam ("seam 3") was deposited near the top of the Cummings Member, indicating a temporary regression of the Clearwater Sea. Another major coal seam ("seam 8") was deposited during late Mannville time. This latter seam is absent, however, between Townships 37 and 39, probably due to non-deposition.

The Battleford Arch passes through the central part of the thesis area. It is present as a topographic high which probably formed a depositional barrier during deposition of the Dina and the Cummings Members. The absence of seam 8 in Townships 37 to 39 is probably also due to this high.

The coal in the Mannville Group is of no commercial value at the present time. It is scattered throughout the Lower Cretaceous sediments. Resources in place are estimated to be approximately 19,400 million (short) tons (approximately 17,600 million metric tons).

ACKNOWLEDGEMENTS

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Chapter 1

INTRODUCTION

A. LOCATION OF STUDY AREA AND SOURCES OF INFORMATION

The area studied in this thesis occupies approximately 8,700 square miles (22,560 square kilometers) in west-central Saskatchewan, extending from Range 18 west of the Third Meridian on the east to the Alberta-Saskatchewan border on the west, with the southern and northern boundaries including Townships 29 and 50, respectively (figure 1.1). Data were obtained from geophysical logs of 236 wells (figure 1.2) with 115 wells having coal occurrences. Another 101 wells were examined in a small area (see figure 8.3) to obtain closely-spaced data for the variogram study.

B. OIL AND GAS FIELDS AND COAL IN THE STUDY AREA

The major oil fields in the area are: Dodsland, Coleville-Smiley, North Hoosier and Lloydminster. The productive zone of the former two fields is the Viking Formation (Lower Cretaceous). In the North Hoosier field (Kindersley area) oil is found in the Middle Bakken Sandstone (Mississippian), Deville Member (Detrital Zone) and Dina Member (Basal Blairmore Sand), of Early Cretaceous age (White, 1974). The Residual Zone Pool, as it is called, in the vicinity of Section 11-31-28 west of the Third Meridian, is the only producing reservoir in the Deville Formation. Oil is commercially produced in the North Hoosier Basal Blairmore Sand Pool in Sections 10 to 15 and 22 to 24, Township 32, Range 27 west of the Third Meridian. The reservoir is several square

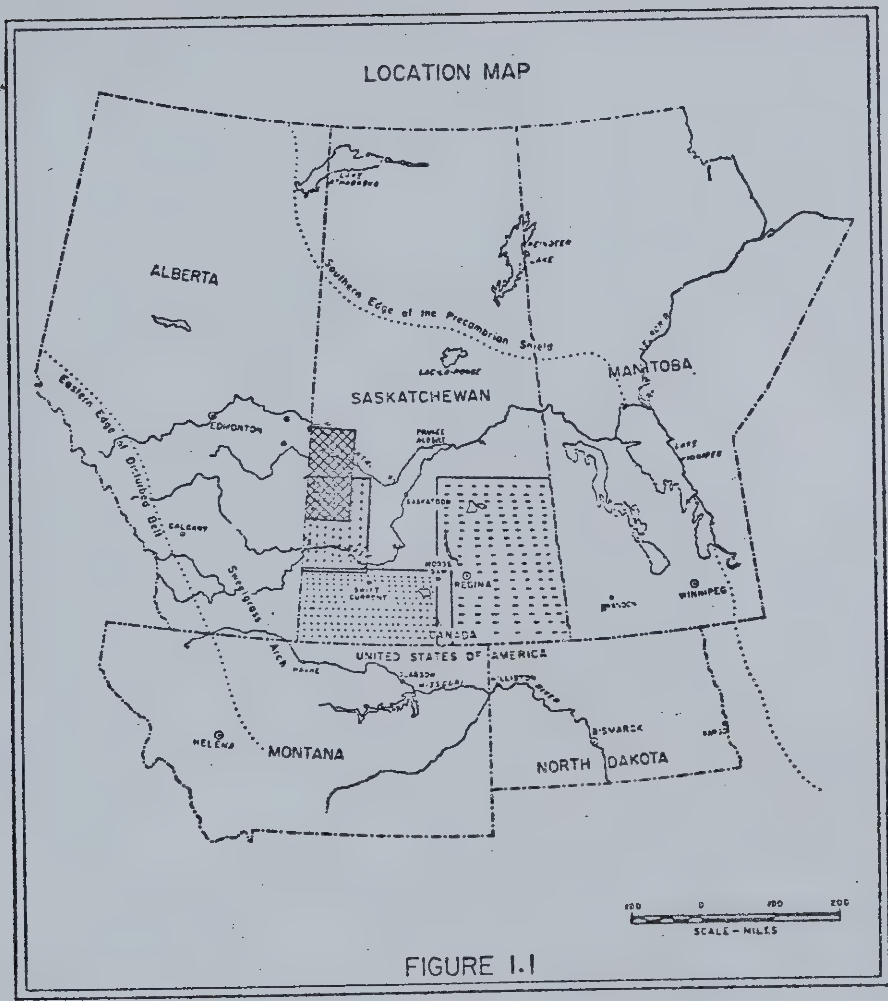


FIGURE 1.1

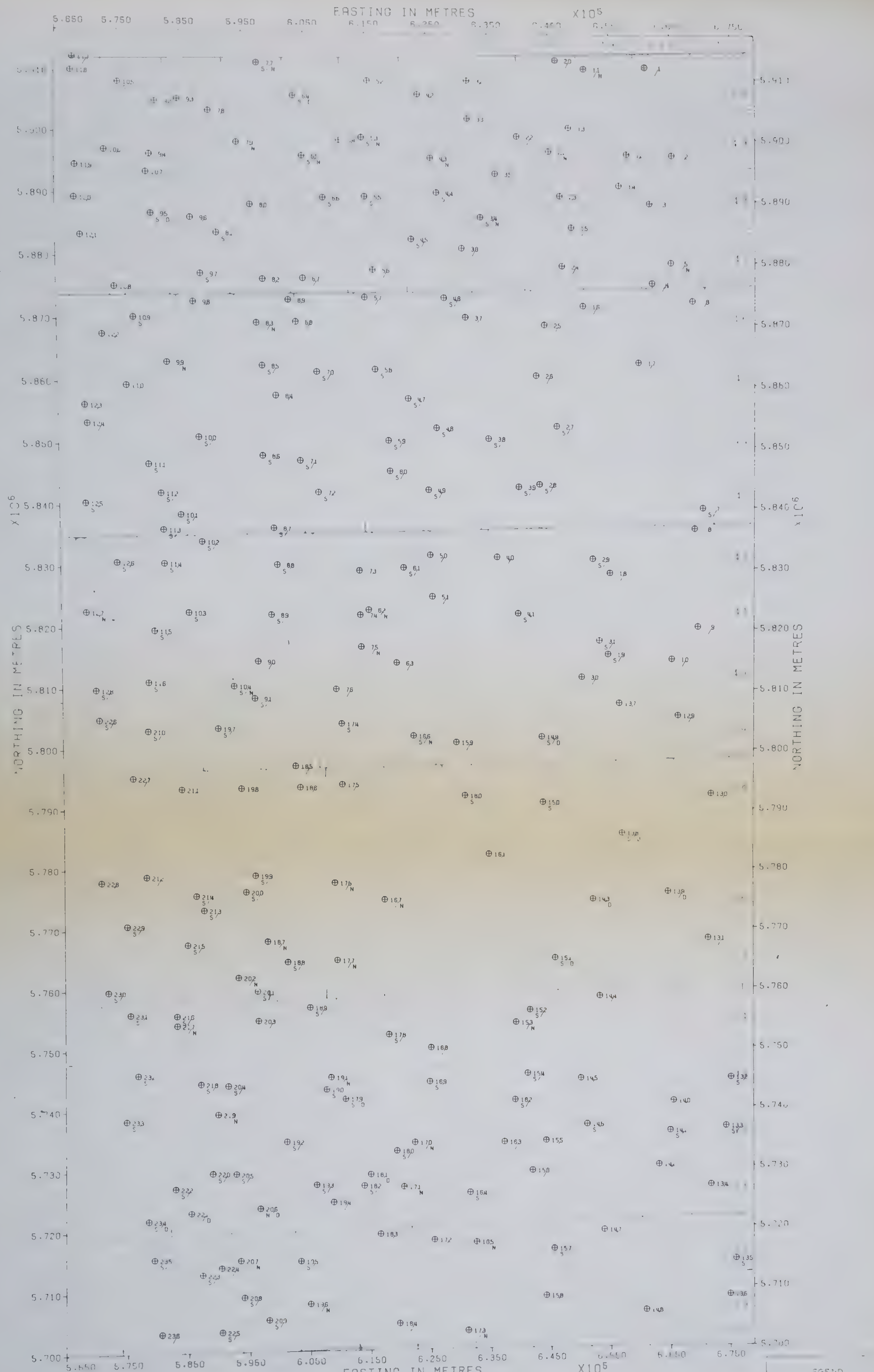
area of study

Maycock, 1967.

Christopher, 1974.

Price, 1962.

Fig 1.1 LOCATION MAP.



CONTROL WELLS LOCATION AND TYPE OF LOG USED.

AREA: TWP.29-30, RGE.18-28 W3.

Fig.1.2

miles in areal extent and is capped by an impervious layer of shale or mudstone and underlain by coal (seam 6). Both pools produce heavy oil with gravity between 13° and 15° API (specific gravity, 0.979 to 0.966). Reasoner and Hunt (1954) suggested that the source for the Bakken and Mannville accumulation was the Mannville sediments.

The North Hoosier field produces 28 percent of Saskatchewan's heavy oil. The remaining 72 percent of heavy oil production is derived from sands of the Mannville Group (mainly the Sparky sand) in the vicinity of Lloydminster.

Altogether, ten coal seams are present within the Mannville Group, but only two (seams 3 and 8) have regional significance. Seam 3 was deposited near the top of the Cummings Member and extends as far south as the member itself (Township 40). Seam 8 covers the northern and southern part of the study area and was deposited on top of the Sparky sand (equivalent to the upper part of the Borradaile Member). The remaining eight seams have very limited local extent; two of which (seams 1 and 2) were encountered only once in the 236 wells studied.

C. PURPOSE OF THE THESIS

Maycock (1967) discussed the geology of the Lower Cretaceous sediments in west-central Saskatchewan, and between Townships 29 and 40, he referred to the Mannville sediments as "Undifferentiated Mannville Group". On the other hand, Nauss (1945) subdivided the Mannville into six members in the Vermilion area, approximately 36 miles west of the northwest corner of the present study area. One of the purposes of this thesis is to find the boundary between these two classifications and what

constitutes this boundary. Correlation between the two classifications based on lithology is evidently inapplicable. Because there is a lack of fossils, using fossils for correlation is not possible at the present time. In this thesis, the writer had chosen coal as a means to explain some of the stratigraphic problems. A number of coal seams do occur both in the northern and in the southern part of the study area, providing a good tool for correlation purposes. The writer had also used coal to gain some insight into the depositional environments. Finally, in order to give an idea of how much coal is present in the Mannville sediments studied, a resources estimate was carried out. To summarize, this thesis project was undertaken in order to:

(1) determine the areal relationships between Maycock's and Nauss' stratigraphic subdivisions,

(2) attempt to determine the causes of the facies changes between Maycock's and Nauss' areas,

(3) study the distribution of coal in the Mannville Group of western Saskatchewan and to determine whether coal distribution can aid in reconstructing depositional environments in the Mannville Group, and

(4) estimate the in-place coal resources of the area mapped.

Chapter 2

PREVIOUS WORK

Because of the hydrocarbon potential of Lower Cretaceous strata in the Lloydminster area, the Mannville Group has drawn much attention recently. Earlier work which deals with the Mannville Group in the study area is limited either in areal extent or in geological aspect. Reasoner and Hunt (1954) discussed the geology of the Coleville-Smiley oil field; Price (1955) extended the term Mannville from Alberta into Saskatchewan. More recently, Maycock (1967) studied the area between Townships 18 and 40, Ranges 15 to 29 west of the Third Meridian in some detail. Studies on local oil and gas pools have also been carried out by Wickenden (1948) and White (1969, 1972, 1974). Other work that deals with neighbouring areas include Nauss' (1945) subdivision of the Lower Cretaceous beds in the Vermilion area based on the presence or absence of dark minerals, Badgley's (1952) description of the Mannville Group in central Alberta, Glaister's (1959) correlation of the Lower Cretaceous of southern Alberta and adjoining areas, Williams' (1963) reclassification of the Mannville Group in central Alberta based on petrographic-stratigraphic evidence and Mellon's (1967) petrographic study of the Mannville Group in Alberta. The most recent work is that of Christopher (1974) in southwestern Saskatchewan in which he recognized a new formation (Success Formation) at the base of the group, below the Cantuar and Pense Formations used by Price (1955) and Maycock (1967).

The name Mannville was first used by Nauss (1945) for a predominantly non-marine formation in the Vermilion area, lying between the

sub-Cretaceous unconformity and the marine Joli Fou shale. The term has been used for the Lower Cretaceous sediments within the Alberta Plains for some time, yet correlative beds are still popularly referred to as Blairmore within the Saskatchewan subsurface. These rocks, however, are both geographically and lithologically different from those of the type Blairmore of the Alberta Foothills. Price (1955) introduced the term Mannville into Saskatchewan and subsequently (1963) showed the areal extent of these strata within the Interior Plains (figure 2.1).

The first estimate of coal resources in Canada was prepared by Dowling (1913) for the 12th International Geological Congress. His estimate of Canada's resources was 1.3 trillion (short) tons, based on coal seams with a minimum thickness of one foot to a maximum depth of four thousand feet. Mackay (1947) reported 99 billion tons of coal in-place in his study for the Royal Commission on Coal in 1946. The reason for Mackay's lower estimate is that he used seam thickness and depth of overburden that varied from coal field to coal field and did not include seams less than three feet thick. Latour and Chrismas (1970) made a more detailed survey on western Canadian coal, using the following parameters:

(1) seams less than three feet thick and rock partings that are one foot thick or thicker are not included in calculating the tonnage,

(2) only coal seams that are within one hundred and fifty feet from the surface are considered.

They estimated a total of 118.7 billion tons of coal in-place in western Canada. Of this, 9.8 billion tons (8.3%) are considered measured resources, 50.3 billion tons (42.4%) indicated and 58.6 billion tons

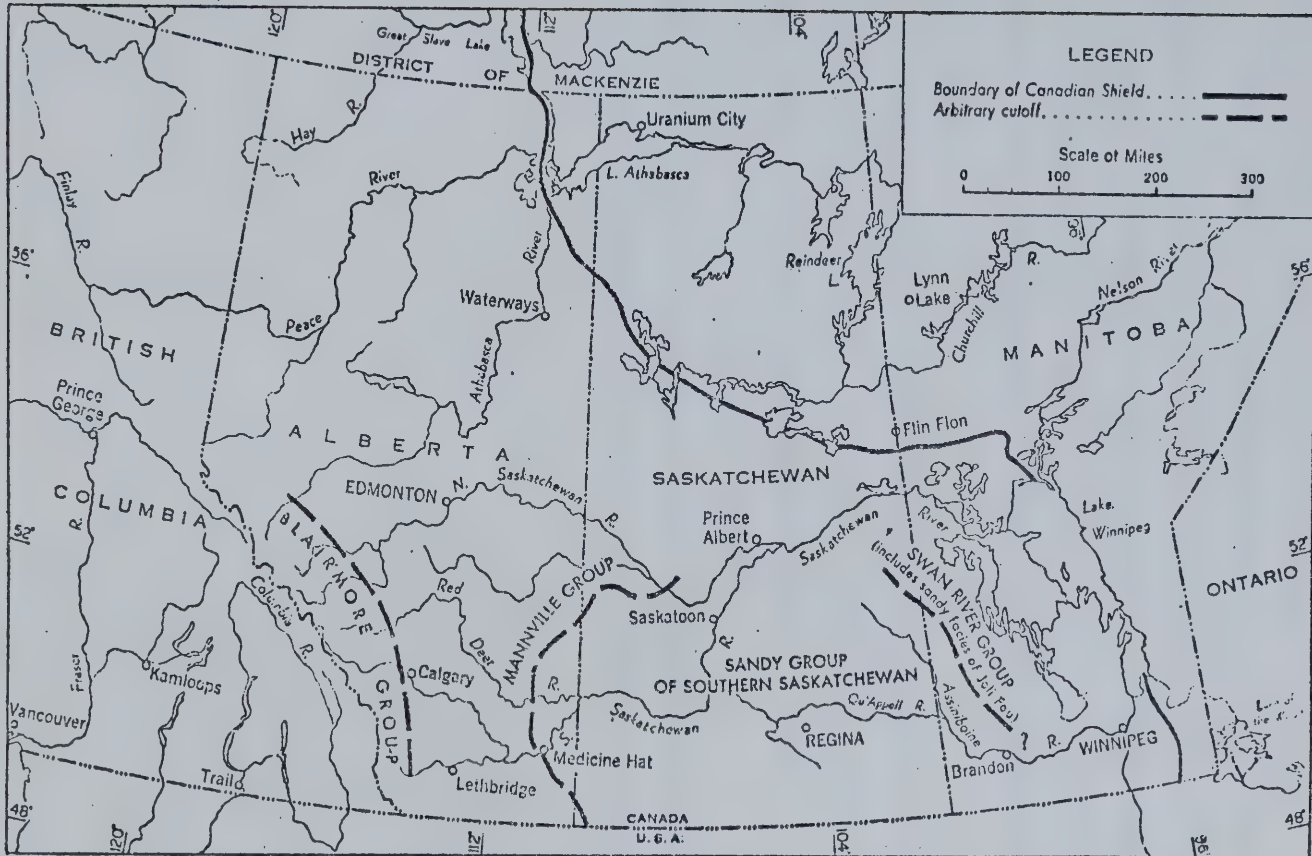


Fig 2.1 PROBABLE GEOGRAPHIC LIMITS of BASAL CRETACEOUS GROUP of CANADIAN PLAINS.*

(*after Price 1962)

(49.3%) inferred. Among the three western provinces, Saskatchewan has 10.1% of the total coal resources in Late Cretaceous to Tertiary (Ravenscrag Formation) beds in the south of the province.

Yurko (1976) surveyed the deep Cretaceous coal resources in the Alberta Plains and estimated a total of 628 billion tons for seams two feet thick or thicker in the Mannville Group. This represents 60% of the estimated total deep coal resources in the Cretaceous System in Alberta. The method used was similar to that used by the writer for this study.

Other than these regional estimates for the western provinces, no data has been published on the estimate of the coal resources in the study area. Coal seams in the Mannville Group are generally thin and about 1,700 to 2,000 feet below the surface. This coal is of no commercial significance at the present time, but could become important if techniques for underground "in situ" gasification are developed.

Chapter 3

METHOD OF STUDY

A. AVAILABILITY OF INFORMATION

Data for this study were obtained from geophysical borehole logs, which were run primarily for oil exploration. Therefore, a complete suite of logs favourable for coal identification was not always available for each borehole. All 236 wells used in the regional study have at least a resistivity log; 95 of the 236 wells have a sonic log; 25 have a neutron log; 5 have a density log; 7 have both sonic and density logs; 6 have both sonic and neutron logs, and 1 has density and neutron logs. In the remaining 97 wells, data were derived solely from the resistivity log. The resistivity log always includes a spontaneous potential (SP) log, and the sonic, density and neutron each include a gamma log.

B. LOG CHARACTERISTICS OF THE MANNVILLE GROUP

The top of the Mannville Group is indicated by the first increase in resistivity on the electrical log below the Viking sandstone. This increase is always accompanied by a corresponding negative deflection of the spontaneous potential (SP) curve (figure 3.1). North of Township 40, approximately 160 feet below the top of the Mannville, a high resistivity zone with high negative SP defines the Sparky sandstone (equivalent to the upper part of the Borradaile Member). The thickness of this sandstone varies and the base is not always distinct. Therefore, only the top was picked for correlation purposes.

The Cummings and Dina constitute the basal members of the Mannville

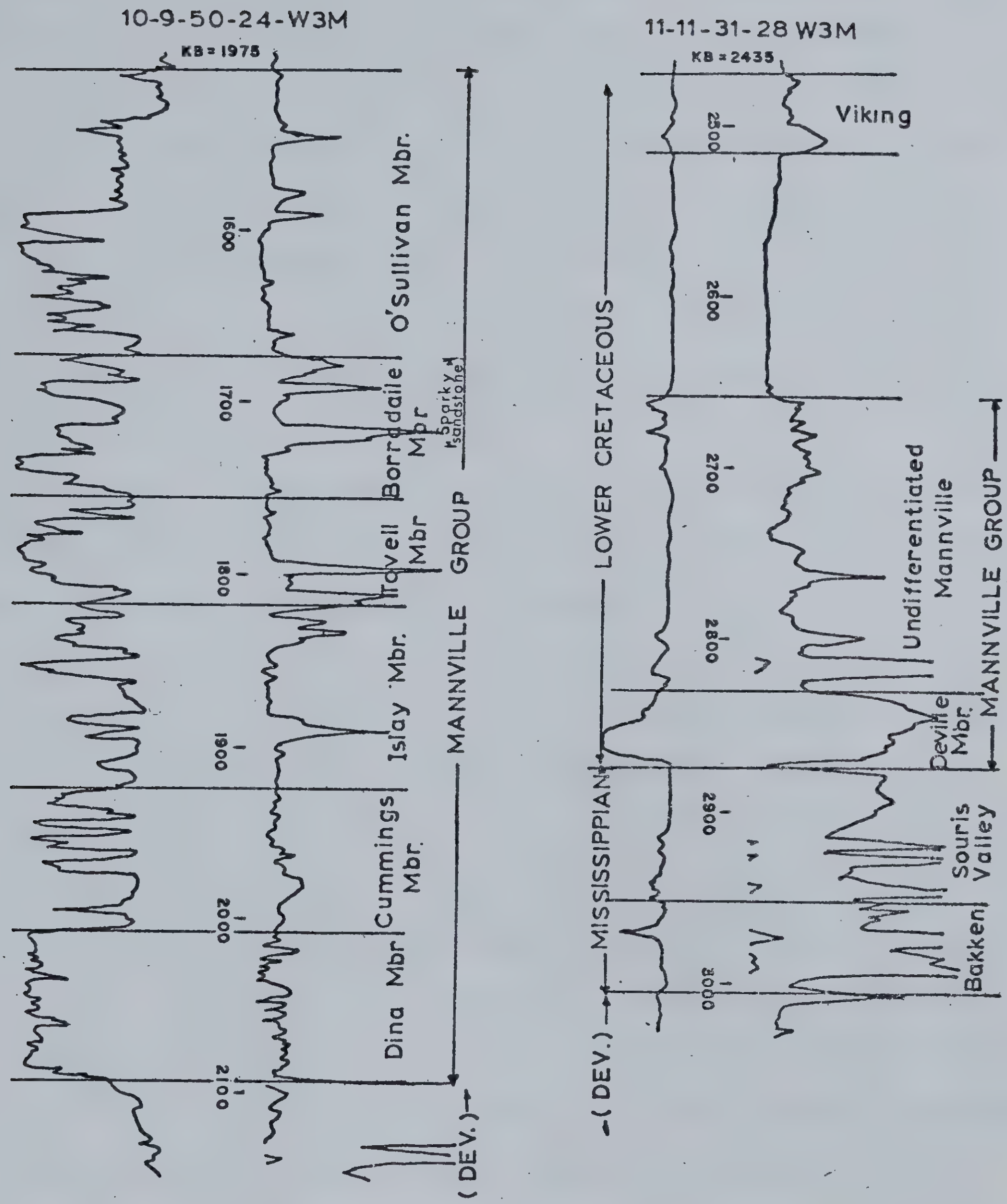
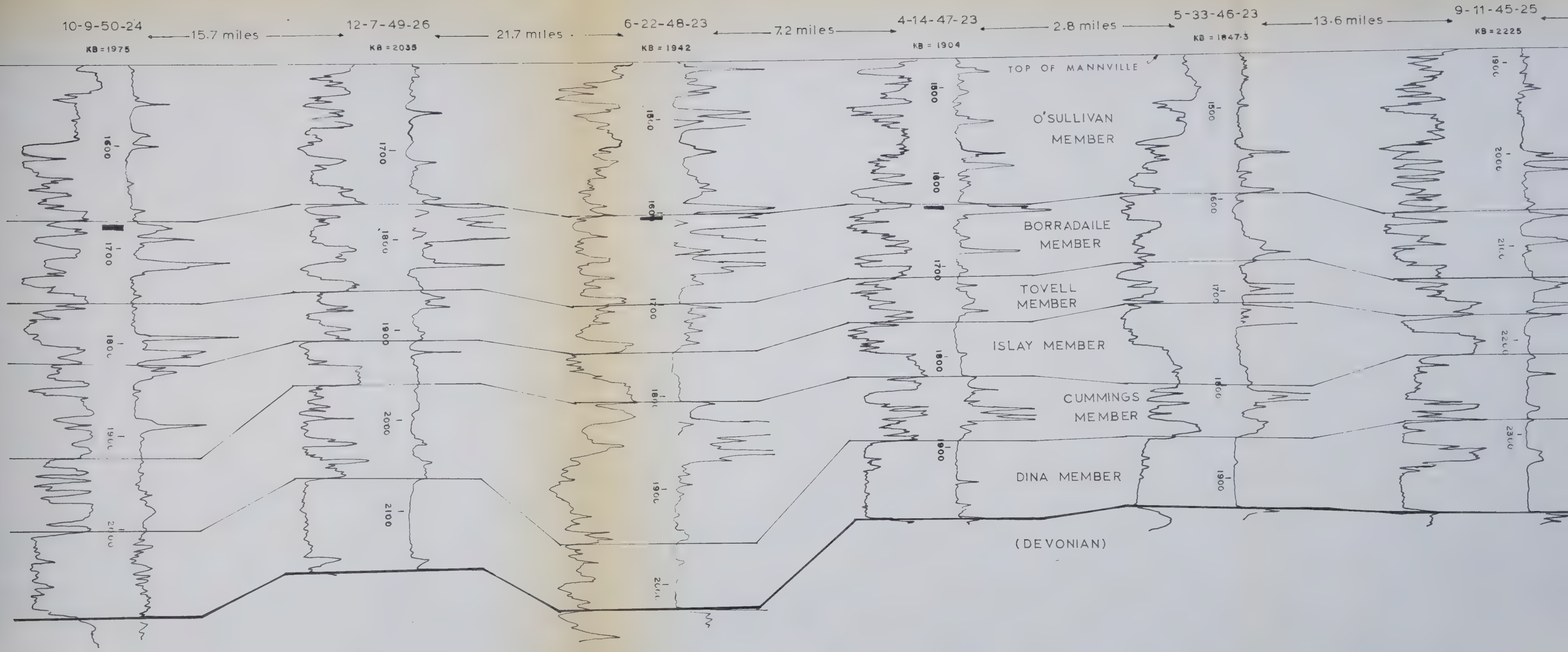


Fig 3.1 LOG CHARACTERISTICS of the MANNVILLE GROUP.

Group. Within the thesis area, the Cummings Member is a sandstone with a high negative SP value and very low resistivity (figure 3.1). These characteristics also apply to the Dina Member. Separating the two is a positive deflection in the SP curve at the base of the Cummings.

The Sparky sandstone and the Cummings and Dina Members lose their distinctiveness from north to south, and south of Township 40 they disappear completely (figure 3.2). South of Township 40, no attempt was made to differentiate the Mannville sediments into individual members, and the writer has adopted Maycock's (1967) designation as "Undifferentiated Mannville Group".

The base of Mannville is easier to pick in the north than in the south. North of Township 35, the Mannville is underlain unconformably by Devonian carbonate rocks with very high resistivity. Since the Dina Member has a very low resistivity, the sharp break in the resistivity curve indicates the position of the sub-Cretaceous unconformity (figure 3.1). South of Township 35, Lower Cretaceous rocks are underlain in places by Mississippian beds, and the boundary between Mississippian and Cretaceous formations is not always clear on the geophysical logs. The Deville Member, if present, has a high negative SP signature, but unlike the Dina, it also has a high resistivity. Mississippian limestones, like those of the Devonian, always show high resistivity and high negative SP, and it is difficult to distinguish between them and the Deville Member. The Mississippian Bakken Formation is subdivided into three (upper, middle and lower) members, each characterized by a distinctive "spike" on the resistivity log. The upper and lower members consist of shale, separated by a sandstone which in places is oil-bearing (figure 3.1).


10-9-50-24
15.7 miles
12-7-49-26
21.7 miles
6-22-48-23
7.2 miles
4-14-47-23
2.8 miles
5-33-46-23
13.6 miles
9-11-45-25
KB = 1975
KB = 2035
KB = 1942
KB = 1904
KB = 1847.3
KB = 2225
TOP OF MANNVILLE
O'SULLIVAN MEMBER
BORRADAILE MEMBER
TOVELL MEMBER
ISLAY MEMBER
CUMMINGS MEMBER
DINA MEMBER
(DEVONIAN)

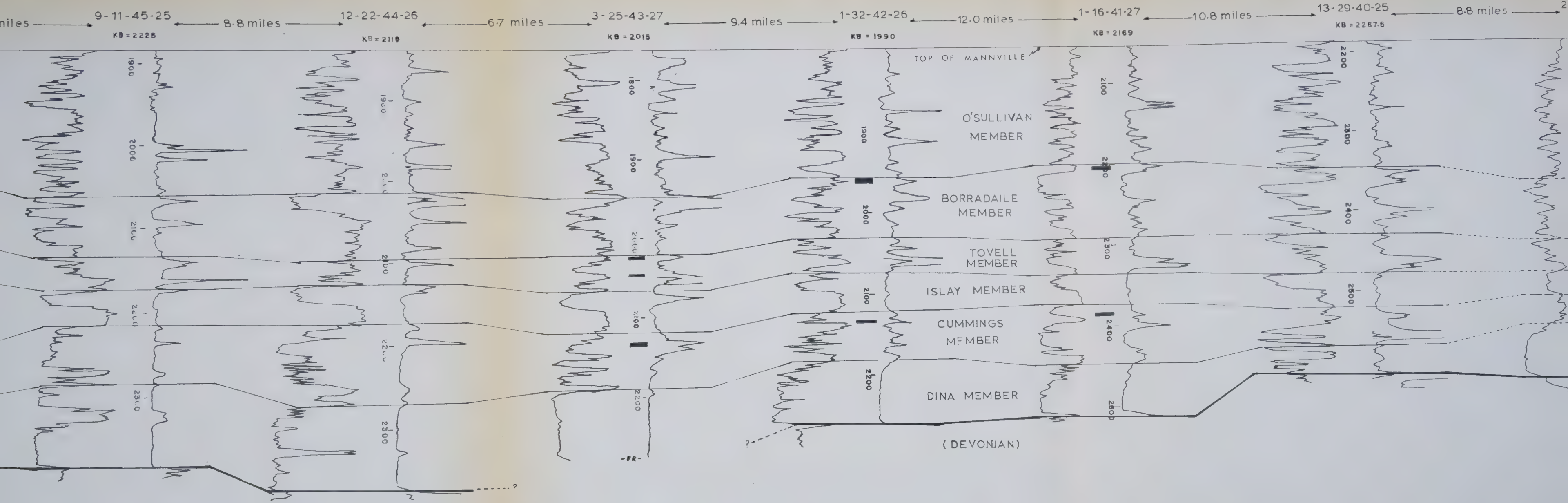


FIGURE 3.2 STRATIGRAPHI
OF THE
MANNVILLE
(DATUM: TOP OF MA

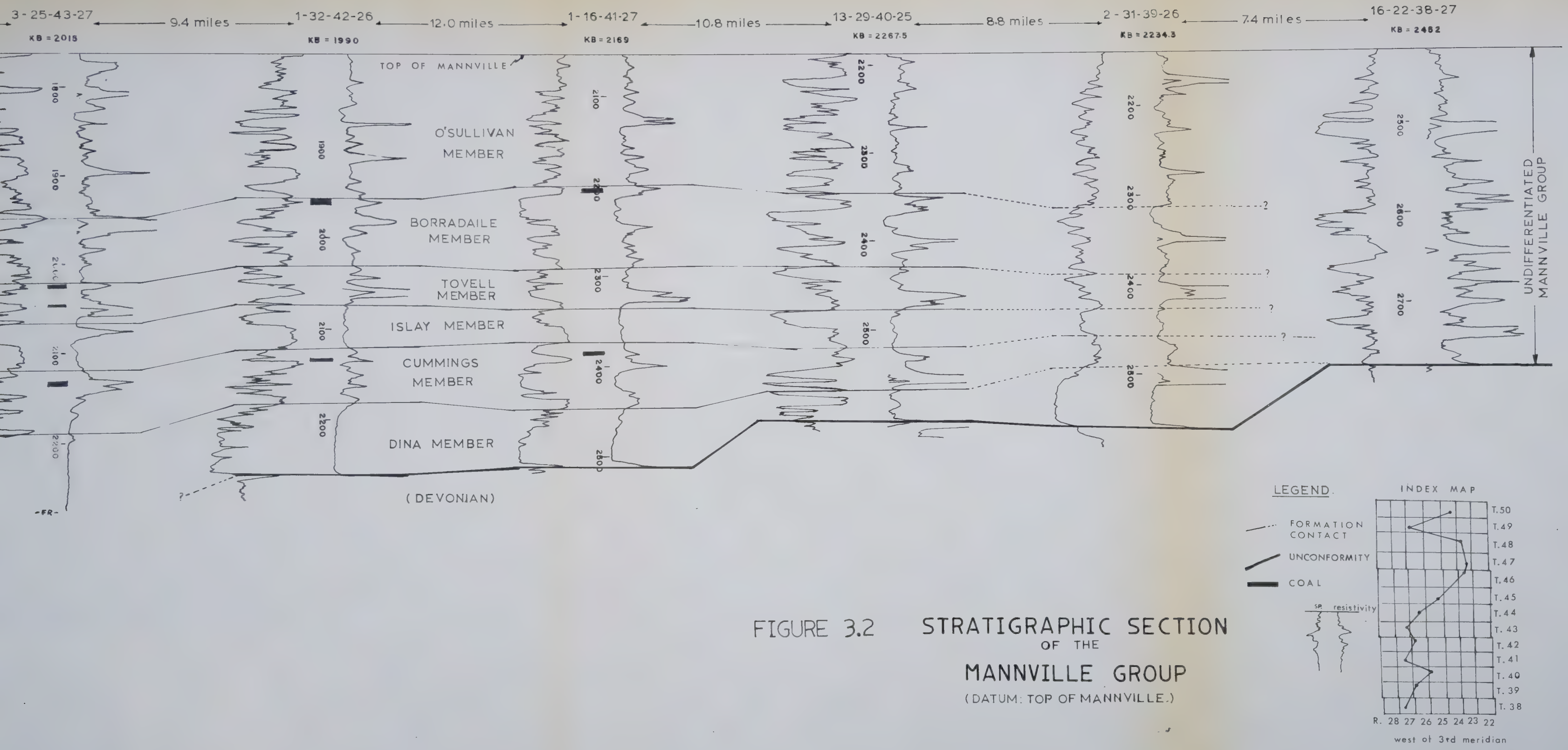


FIGURE 3.2 STRATIGRAPHIC SECTION OF THE MANNVILLE GROUP

(DATUM: TOP OF MANNVILLE.)

C. LOG CHARACTERISTICS OF COAL

Coal has a very characteristic signature on geophysical logs and a detailed discussion on this topic has been published by Bond et al. (1969) (see also Yurko, 1976). The following account is a summary of some of the diagnostic properties of coal in borehole interpretation (see also figure 3.3). Figure 3.4 shows a composite log of the relative position of the coal seams in the study area.

1. Density

Coal densities range from 1.29 to 1.8 gm/cc, depending on the rank, depth of burial, and ash and moisture content. Coal in the Mannville Group is approximately 1,500 feet underground and has a density of 1.8 gm/cc or less. Therefore, when a density log is available, coal is easily recognized by a very low density response as compared to adjacent sandstones and shales.

2. Sonic Log

The sonic log records the interval transit time (ΔT) in microseconds per foot, the time required for a compressional sound wave to travel across one foot of formation. The ΔT value for coal is usually greater than that for shale or sandstone and varies inversely with degree of compaction. That is, coal seams closer to the surface have a longer interval transit time than deeper ones. Tertiary lignite coals of southwestern Alberta and Saskatchewan have ΔT values between 140-170 microseconds per foot, and coals in the Mannville (this study) have ΔT values between 120 and 160 microseconds per foot.

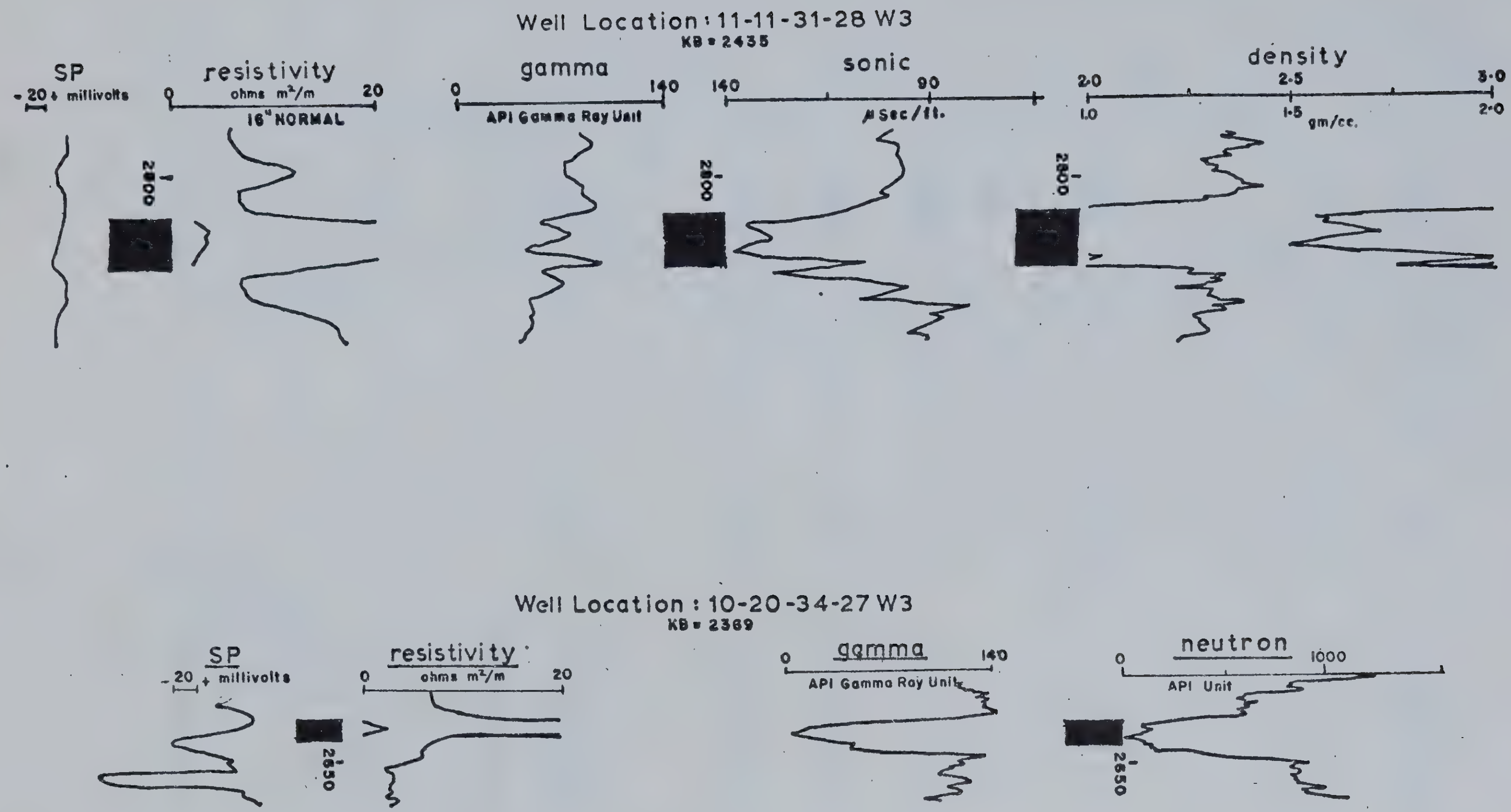


Fig 3.3 LOG CHARACTERISTICS of COAL.

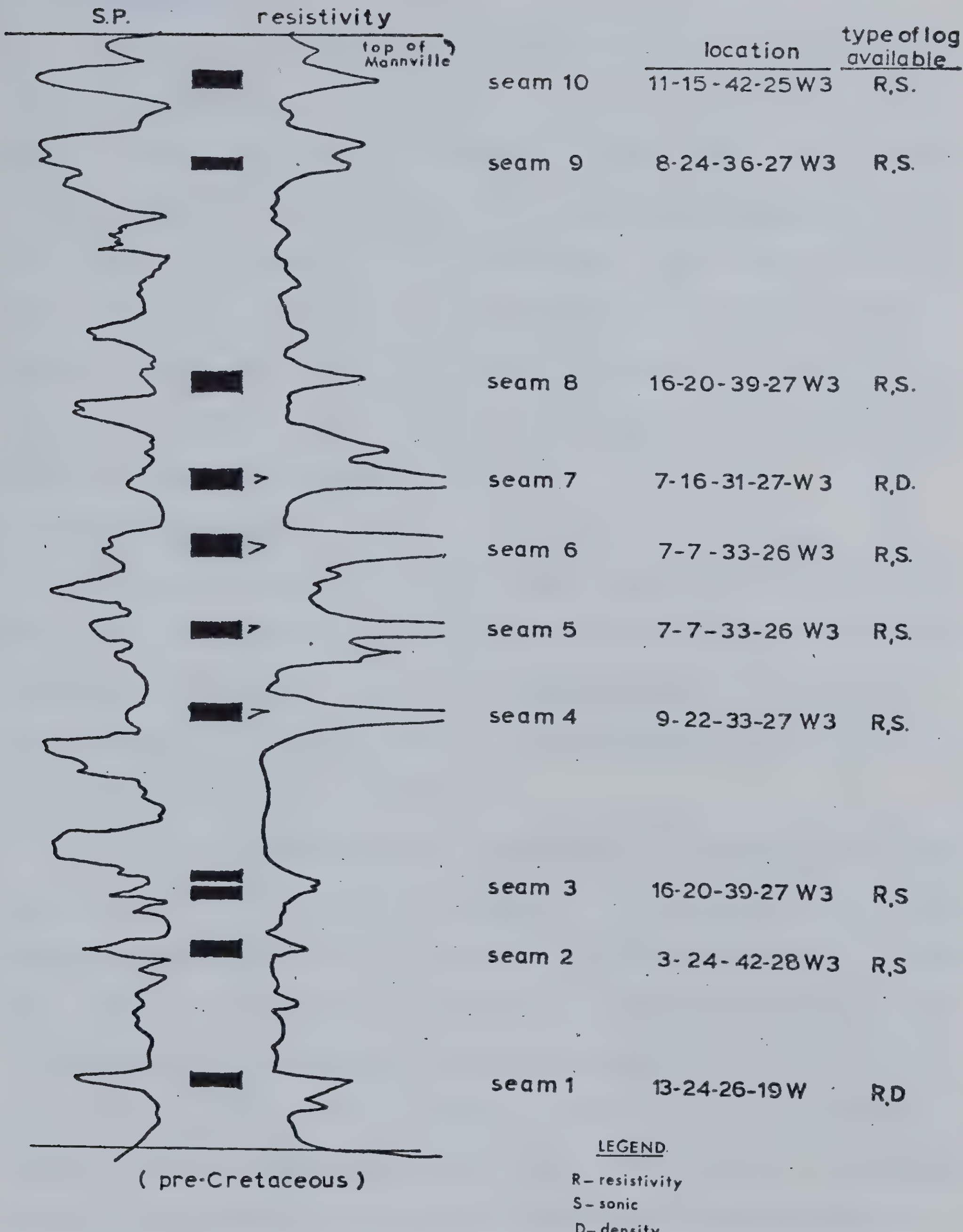


Fig 3.4 COMPOSITE LOG SHOWING RELATIVE POSITION of SEAMS.

3. Neutron Log

The neutron log primarily measures the effectiveness of a formation to moderate or slow down a beam of fast neutrons. Essentially, the moderation of the fast neutrons is caused by hydrogen atoms in pore fluids; however, carbon is also an effective moderator and consequently coal is indicated by low readings on the neutron curve. Unlike sonic or density logs, the neutron log does not have a definite value range to indicate the presence of coal, therefore in using the neutron log to detect coal seams, one has to look for relative low values in the curve rather than absolute values of the neutron count.

4. Natural Gamma Log

Geophysical logs record only the natural gamma radiation in a well bore, which is produced by potassium, uranium and thorium in sedimentary rocks (mainly in shale). Coal, as an organic sediment, contains very small quantities of these elements, therefore has very low radioactivity.

5. Resistivity Log

A relatively high, electrical resistivity is characteristic of clean coal; however, the actual value recorded on a log depends on the ash and moisture content of the coal. Dirty coal, carbonaceous material and even woody fragments may produce low resistivity values on the electrical log.

Coal beds are indicated by high resistivity spikes on the lateral curve with adjacent very low readings in the blind zones immediately below the coal. On normal resistivity curves, if the coal beds are thinner than the electrode spacing, reversals (low readings) generally occur opposite coal beds.

6. Spontaneous Potential (SP) Log

No definite response is registered opposite a coal bed although in the Mannville Group most seams show a slightly negative SP. The spontaneous potential registered on the SP curve depends mainly on the resistivity and thickness of the coal bed, the resistivity and the diameter of the zone contaminated by mud filtrate.

D. RELIABILITY INDEX

With a combination of resistivity and other logs, coal can be identified with a degree of certainty which can be indicated by a numeric reliability index (see Yurko, 1976, pp. 11-12). In this thesis, the writer chose to use reliability indexes 1, 3 and 5, corresponding to indexes 1, 3 and 5 used by Yurko (1976), with the following criteria used in assigning these numbers.

(1) Reliability index 1: coal picked from an electrical log and at least two of the following specific curves:

- (a) natural gamma,
- (b) sonic (acoustic),
- (c) density,
- (d) neutron.

Probability of coal actually being present is estimated to be greater than 90%.

(2) Reliability index 3: coal picked from an electric log, and neutron or natural gamma log. As mentioned previously, no specific value range is assigned to the neutron count for coal beds and picks depend solely on the shape of the curve. The probability of coal actually being present is estimated to be between 50 and 75%.

(3) Reliability index 5: coal picked from an electrical log only. In this case, the probability of coal actually being present drops to 25% or less.

The reasons for not using reliability indexes 2 and 4 as defined by Yurko (1976) are that the geophysical logs used in this study are of relatively good quality and the log characteristics of coal are relatively well defined. Using the tops of the Sparky, Cummings and Dina Members as markers, coal seams within the Mannville Group were correlated and each seam numbered from 1 to 10 in ascending order of the seams.

E. GENERAL DISCUSSION OF COMPUTER APPLICATIONS

The data obtained from the geophysical logs were put into a computer file from which subsequent data files were built to meet the needs of particular application programs. The plotting of contour maps was done by using the "CGRID1" and "CONTUR" plotting subroutines available from the Computing Services program library at the University of Alberta. The CGRID1 routine accepts as input the irregularly distributed borehole data and produces a regular data grid. The number of grid points (i.e., the size of the grid cell) over a map area is controlled by the user; to obtain good results it is advisable to have at least one data point per grid cell. The output from CGRID1 is used as the input to CONTUR which prepares the maps for subsequent plotting on the Calcomp Plotter. CONTUR allows the user to control the number of contours, contour interval and the labelling of the contours. The title, scale and axis of the maps were done using other plotting subroutines, also available from the subroutine library.

Well location maps were generated by using the Generalized Map Posting Routine (GPR) from the Western Canada Coal Resources Data Base Project.

A small area seven miles east of Lloydminster was chosen by the writer for a detailed study of areal variance of coal seam thickness. One hundred and one well logs were studied and the data were used to generate statistical tables and variograms in graphical form (see Chapter 8). A concise account of the theory and application of areal variance studies is given by David (1974) and Matheron (1963). A brief summary will be presented in Chapter 8.

Chapter 4

STRATIGRAPHY

A. INTRODUCTION

Studies by several workers lead to the conclusion that the Mannville sediments in the northern plains of Canada can be subdivided into three major portions - a marine shaly unit (equivalent to the Clearwater Formation) which is sandwiched between a lower relatively homogeneous sandy unit (the McMurray Formation) and an upper, more heterogeneous sandy unit (the Grand Rapids Formation).

The lower sandy unit fills in the topographic lows on the sub-Cretaceous erosion surface. In the Interior Plains, the roundness of the quartz grains and the absence of dark minerals in this unit suggests a high degree of maturity and an eastern source area. The overlying shaly unit was deposited during the invasion of the boreal Clearwater Sea. One of the intentions of the writer is to determine the location of the shoreline within the study area. With the withdrawal of the Clearwater Sea and the increase in tectonic/igneous activity in British Columbia, the upper heterogeneous sandy unit was deposited with its main source from the west. As might be expected, this sandy unit has a high content of feldspar and volcanic rock fragments.

Where Mississippian rocks crop out on the sub-Cretaceous surface, their weathered products constitute a distinct cherty unit (the Deville Member) below the relatively homogeneous sandy McMurray Formation.

Nauss (1945) first applied the term "Mannville" to Lower Cretaceous sediments in the Vermilion area. He subdivided the Mannville Formation

into six members as follows in order of increasing age: O'Sullivan, Borradaile, Tovell, Islay, Cummings, and Dina (figure 4.1). This subdivision can also be applied to the northern plains of Saskatchewan. In central Saskatchewan, Maycock (1967) called the correlative sediments "Undifferentiated Mannville Group", and further south, these beds interfinger with the Cantuar and the Pense Formations of Price (1963). The dividing line between the six-member Mannville Formation as defined by Nauss (1945) and the Undifferentiated Mannville Group of Maycock (1967) lies within the present study area, in the vicinity of Township 40 (figures 3.2 and 4.2). Therefore, the study area can be divided into northern and southern portions with Township 40 as the boundary for discussion purposes.

B. THE NORTHERN AREA

North of Township 40, the Mannville Group within the study area can be subdivided into the six members recognized by Nauss (1945) (figures 4.1 and 4.2). The Dina Member appears as a uniform clean sandstone on the SP log (figure 3.1). It fills in the palaeo-topographic low areas, and pinches out southward towards Township 40 (figure 4.3). After deposition of the Dina Member, the boreal Clearwater sea transgressed southward and deposited the Cummings Member which also thins towards the south and pinches out in the vicinity of Township 40 (figure 4.4). The maximum thickness of the Clearwater occurs in both the northeastern and northwestern corners of the map area. The shoreline at that time probably trended east-west through the study area, and to the west turned north towards Wainwright where the Cummings is also absent (Nauss, 1945).

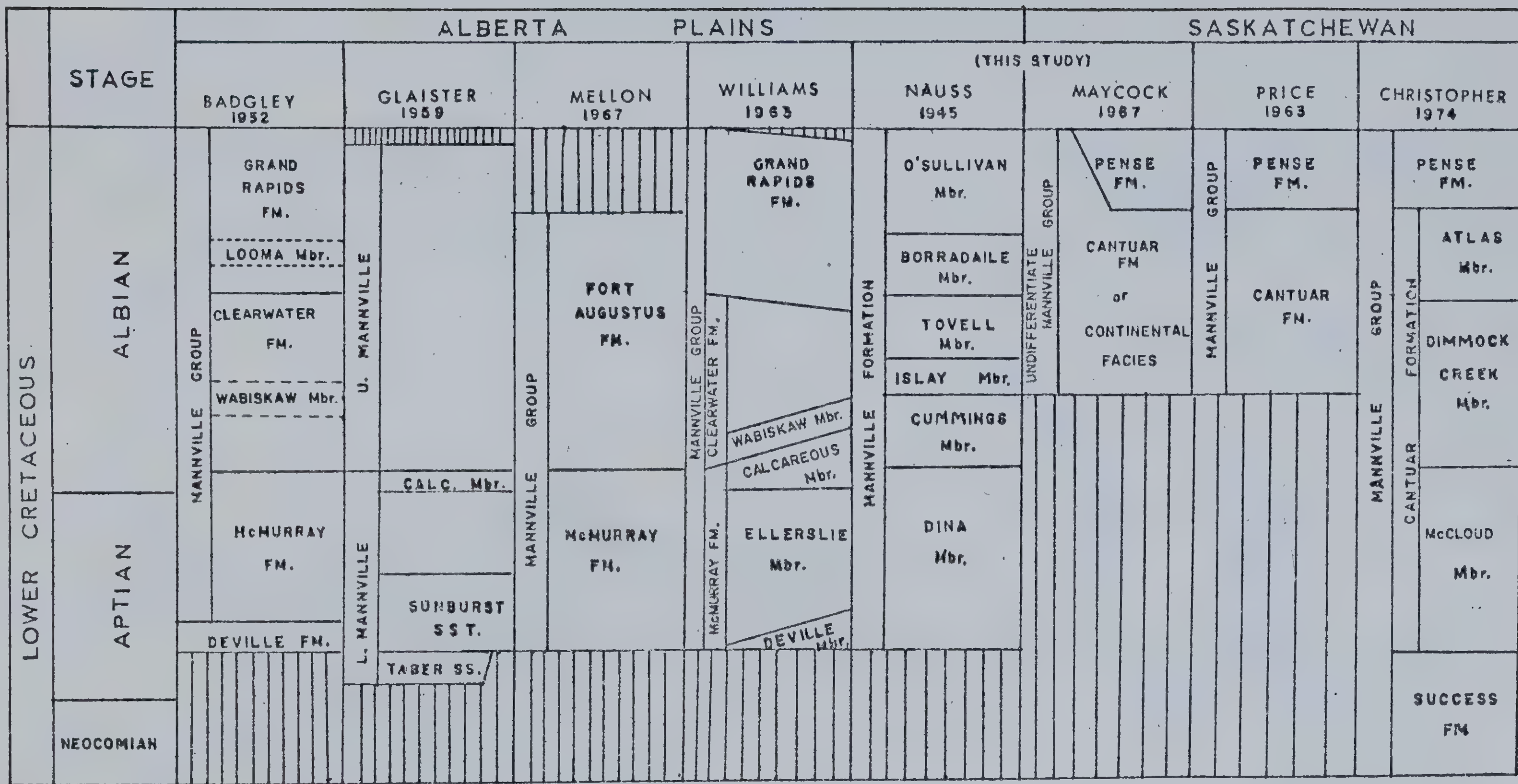


Fig. 4.1 TERMINOLOGY of LOWER CRETACEOUS ROCK UNITS in the INTERIOR PLAINS.

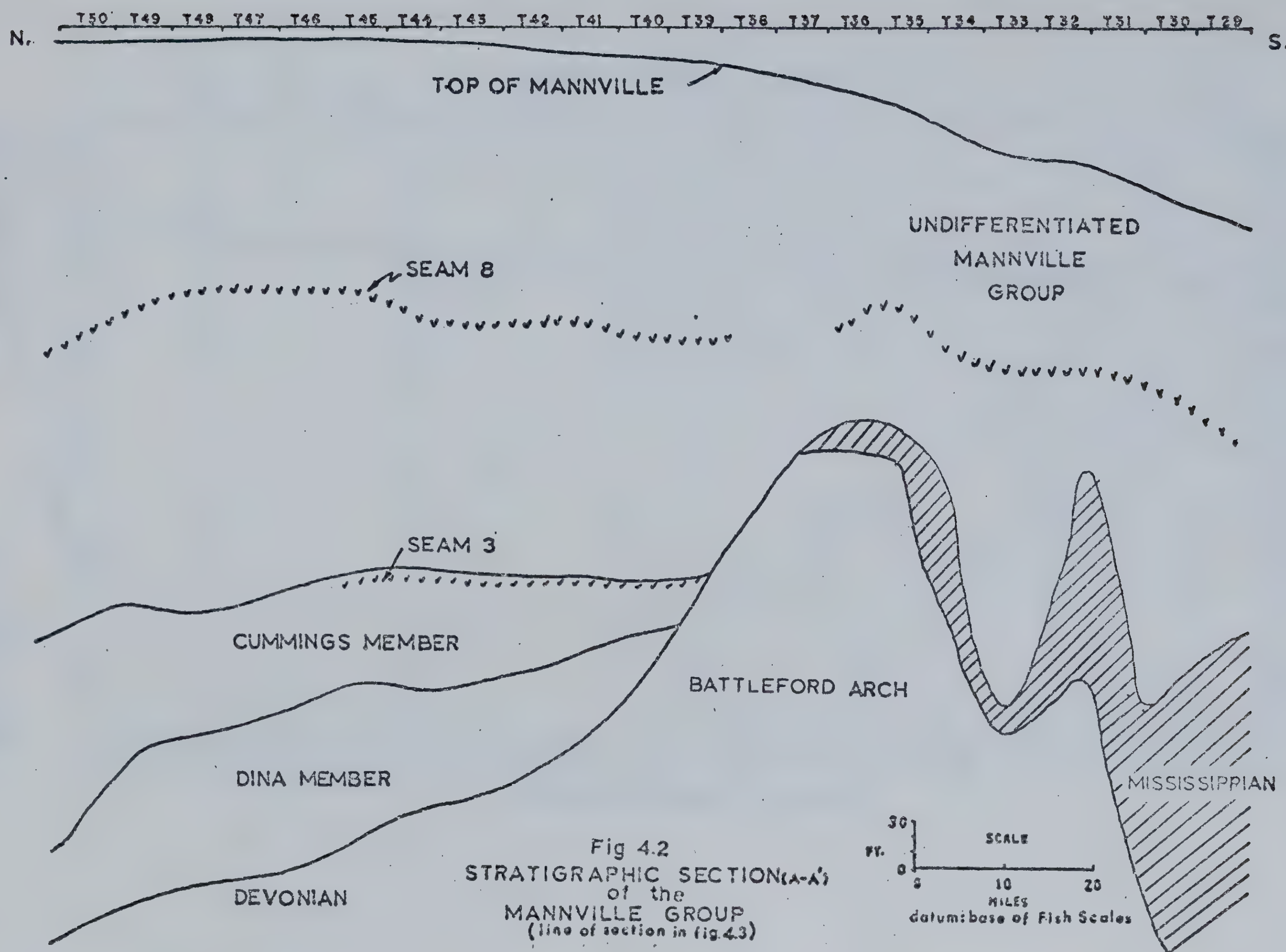
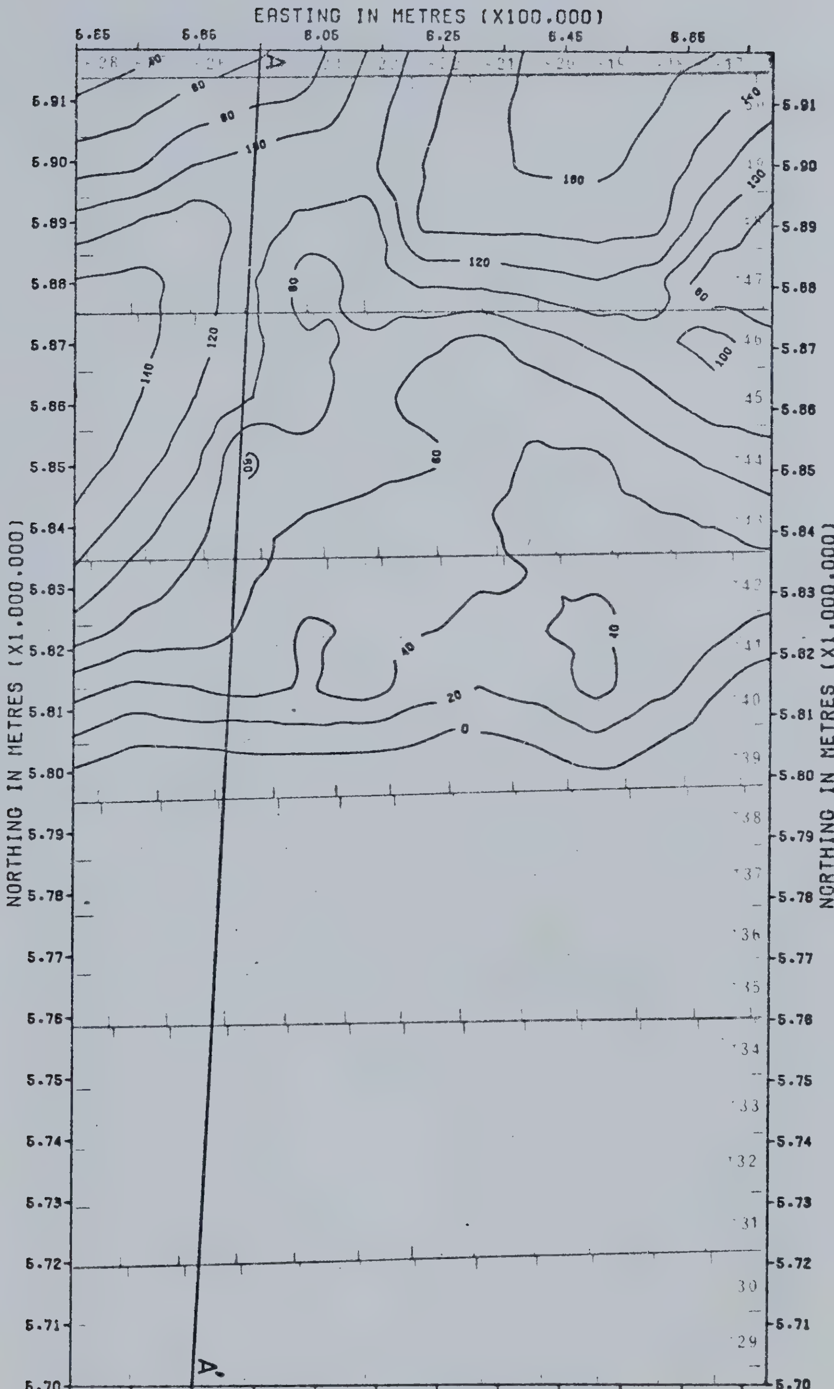


Fig 4.2
STRATIGRAPHIC SECTION (A-A')
of the
MANNVILLE GROUP
(line of section in fig. 4.3)

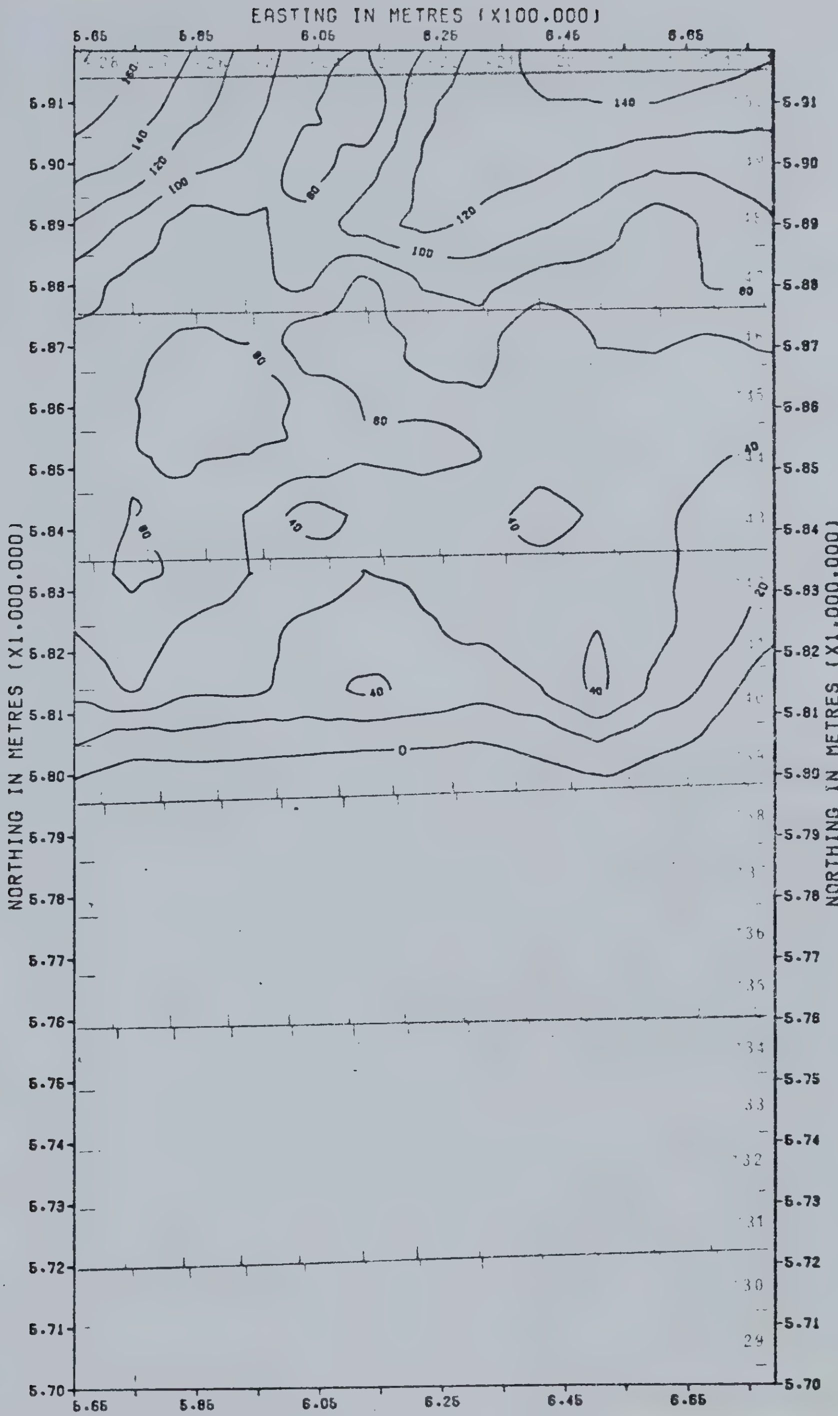


ISOPACH MAP OF THE DINA MEMBER.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 20 FT.

SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

Fig. 4.3



ISOPACH MAP OF THE CUMMINGS MEMBER.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 20 FT.

SCALE 0 1 2 3 (X10KM) 0 10 20 (MILES)

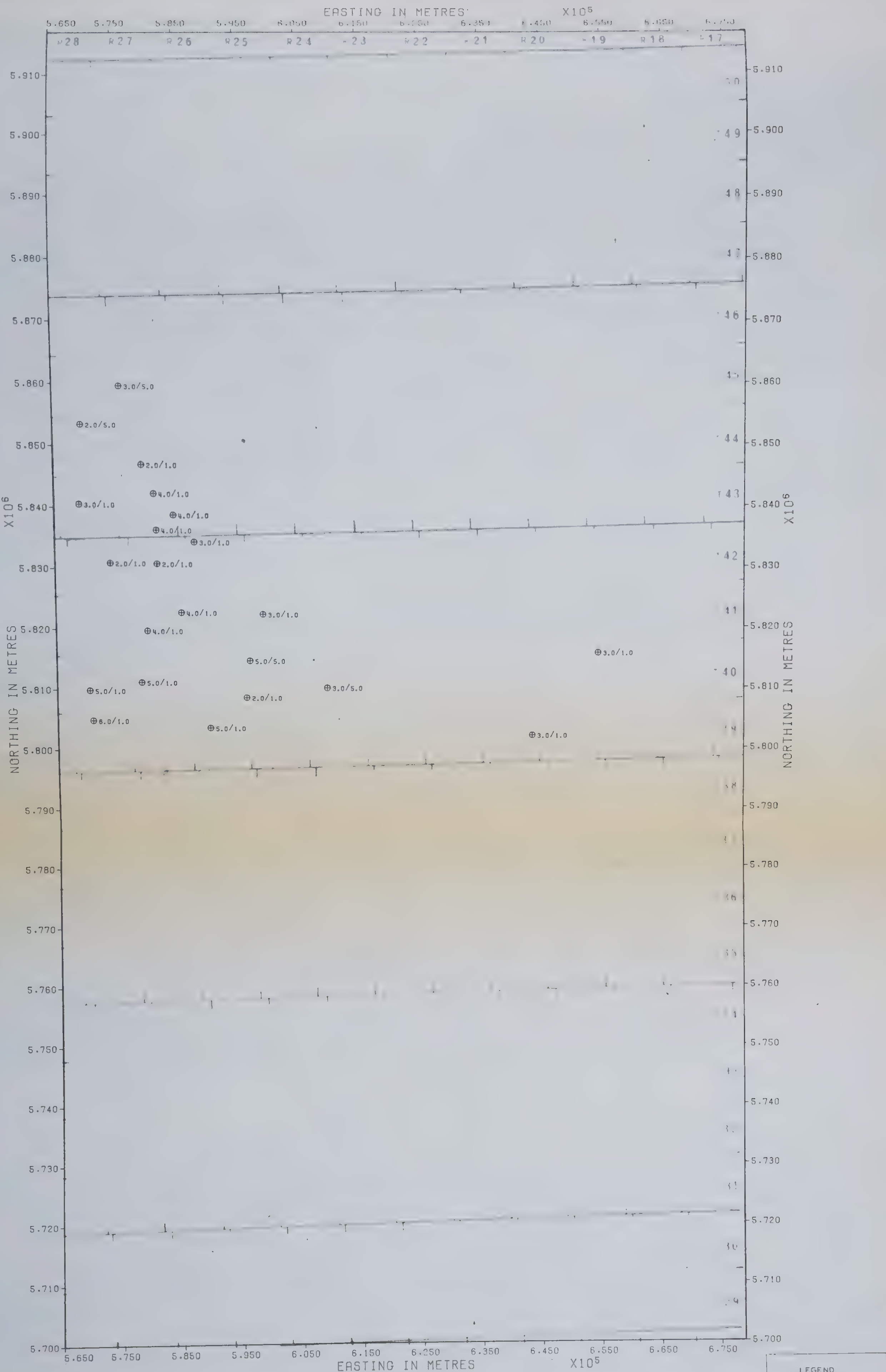
Fig.4.4

A coal seam (seam 3) near the top of the Cummings Member is limited to Townships 40 to 45, Ranges 24 to 28 west of the Third Meridian (figure 4.5). The presence of this seam and the sandy lithology of the Cummings in the study area indicate that the area was probably near shore and that a temporary regression of the Clearwater sea occurred during the deposition of the member.

The remaining portion of the Mannville sediments can be subdivided into the Islay, Tovell, Borradaile, and O'Sullivan Members (figure 3.2). All of them have a southern depositional limit in the vicinity of Township 40. A major coal seam (seam 8) at the top of the Borradaile Member ("Sparky sandstone" in oil industry terminology) was used as a marker horizon. Its distribution is shown in figure 4.6.

In east-central Alberta, the Dina Member as described by Nauss (1945) consists mainly of quartz sandstone containing rounded, frosted grains, interbedded with siltstone and shale. Dark minerals are rare. The overlying Cummings Member is principally dark grey to black shale. As the Clearwater sea regressed, the Islay Member was deposited along its beaches (Nauss, 1945, p. 1627). The overlying Tovell, Borradaile and O'Sullivan Members have lithologies indicating an alternation of deltaic and near shore environments.

The upper portion of the Borradaile Member is the productive sand in the Borradaile oil field. Wilson (1947) noted a regionally widespread coal seam at the top of his "Upper Wainwright" unit (equivalent to the Borradaile Member), about 130 to 145 feet below the top of the Mannville and called it the "Wainwright coal". This same coal seam was picked as seam 8 by the writer.



DISTRIBUTION OF SEAM 3.

AREA: TWP.29-50, RGE.18-28 W3.

Fig. 4.5

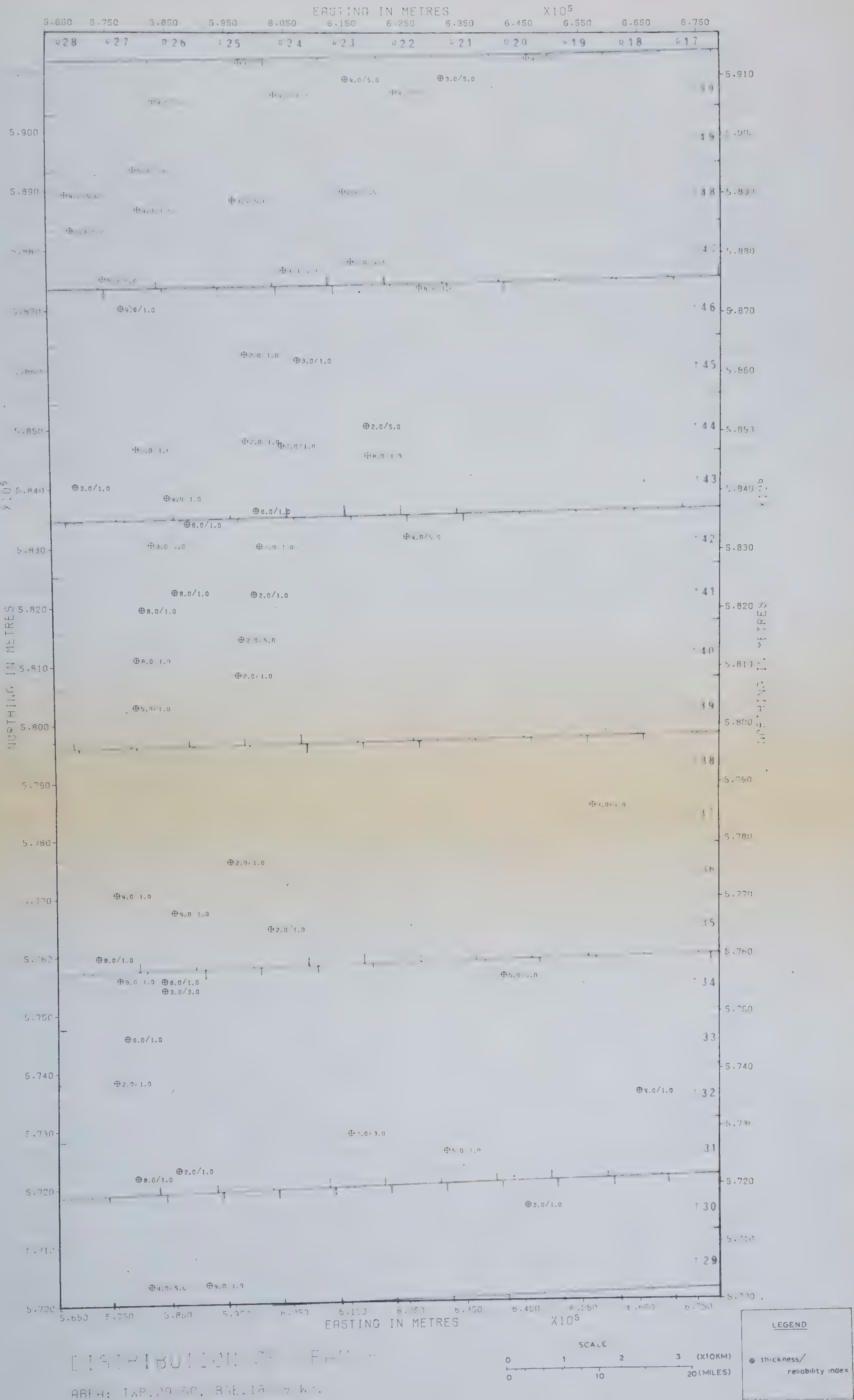

EASTING IN METRES
X10^5
NORTHING IN METRES
LEGEND
⊕ thickness/ reliability index
SCALE
0 1 2 3 (X10KM)
0 10 20 (MILES)

Fig. 4.6

In central Alberta, the Mannville Group was divided, in ascending order, into the McMurray, Clearwater and Grand Rapids Formations by Badgley (1952). The McMurray Formation, correlative to the Dina Member, is composed of the Deville, Ellerslie and Calcareous Members. The Deville Member is the weathered product of the underlying Mississippian and Devonian rocks. The main facies of the McMurray Formation is the Ellerslie Member ("Basal Quartz") which is composed mainly of quartz sandstone with minor siltstone, and silty, often carbonaceous shale. It is texturally and compositionally mature, and the sediments have gone through several depositional cycles (Williams, 1963). Williams et al. (1962, p. 324), using K-Ar dating on the detrital feldspar from the McMurray Formation, concluded that the "... K-Ar dates ... indicate Precambrian sources on the Canadian Shield ...".

The top unit of the McMurray Formation is the Calcareous Member (Glaister, 1959), characterized by abundant invertebrate remains including pelecypods, gastropods and ostracodes of non-marine and near-marine origin (Mellon, 1967). As a lithologic unit, it is also commonly known as the "Ostracode Zone", and has been dated as late Aptian or early Albian in age (Glaister, 1959). The Calcareous Member is absent in the study area and the Dina Member is overlain by the Cummings Member.

The Clearwater sea transgressed into central Alberta where the Clearwater Formation (Williams, 1963) was deposited. The Clearwater-McMurray contact, as well as the Clearwater-Grand Rapids contact, are probably diachronous (see Williams, 1963, figure 8; and Mellon, 1967, p. 64). For this reason and the fact that the Clearwater Formation

cannot be distinguished as a separate entity over much of central Alberta, Mellon (1967) combined the Clearwater and the overlying Grand Rapids Formation into the Fort Augustus Formation.

The Clearwater Formation in the Edmonton area is composed of the basal Wabiskaw Member (commonly known as "Glauconitic Sandstone") and the overlying dark grey shale. Mellon (1955) suggested that the glauconitic sandstone is an offshore bar deposit (figure 4.7). Both the Calcareous Member and the "Glauconitic Sandstone" are absent in east-central Alberta and in the study area. Nauss (1945, p. 1627) hypothesized that: "After the Cummings epoch the sea receded and on its beaches originated the glistening sands of the Islay Member." This indicates that the Vermilion area was emerging while deposition of the Clearwater Sea continued in central Alberta. If this is the case, Badgley's (1951) correlation of the "Glauconitic Sandstone" with the Islay Member is questionable.

The Grand Rapids Formation is the uppermost unit of the Mannville Group in central Alberta and is mainly of non-marine origin. In the Edmonton area, its base interfingers with the Clearwater Shale and is diachronous, being older towards the south (Williams, 1963). Williams et al. (1962) dated two samples of detrital feldspar from the Grand Rapids Formation in Alberta at 120 to 150 and 160 to 220 million years, dates which fall within the range of ages from early Mesozoic intrusions in the central Cordillera.

In southern and central Alberta, the Grand Rapids Formation is included in the Fort Augustus Formation by Mellon (1967) and in the Upper Mannville by Glaister (1959). Both reported the formation as

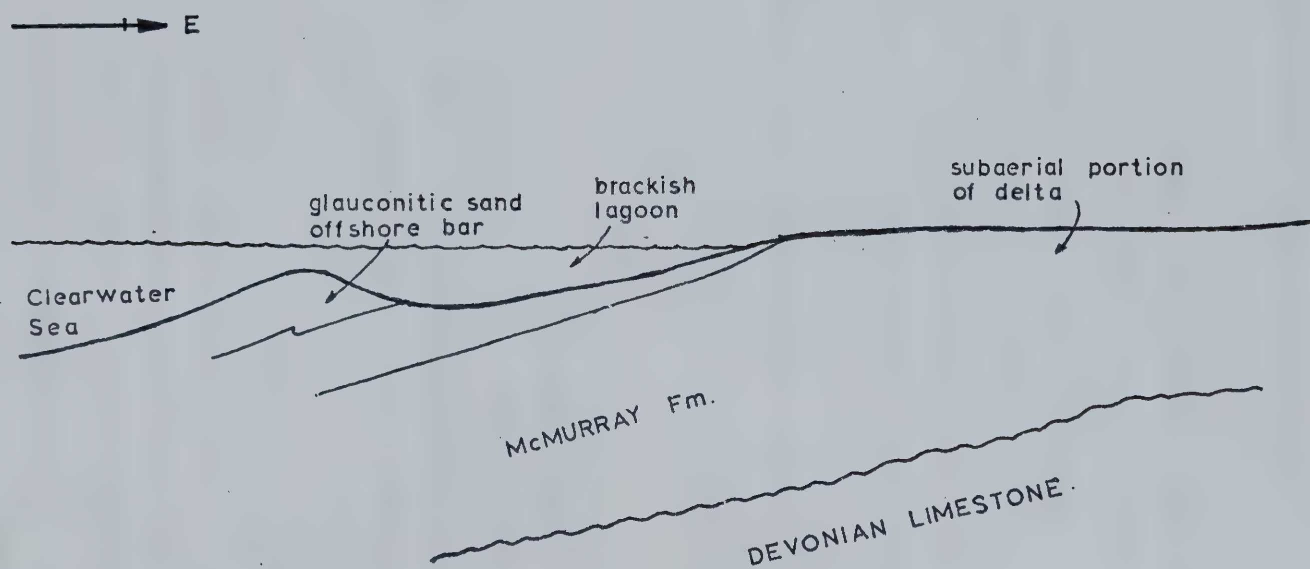


Fig. 4.7 DIAGRAMATIC SKETCH SHOWING DEPOSITIONAL ENVIRONMENTS of ONLAPPING CLEARWATER SEA OVER SUBMERGING McMURRAY DELTA.*

(*after Mellon, 1956)

being mainly of continental origin. According to Mellon (1967, p. 65), "Foraminifera are absent from the Brook Stanmore No. 1 well [Sec. 22-30-11 W4M], where the entire formation appears to be of non-marine origin, and also from the West Viking No. 1 well [Sec. 11-48-15 W4M], although the shale at the base of the formation there appears to be marine ...". Farther north in the Edmonton area (Twp. 51 to 56) the same writer observed foraminifera in the lower and central parts of the formation, which probably occupy a stratigraphic position similar to that of the Clearwater Formation of Williams (1963). The top 140 feet of the formation include coal-bearing strata interfingered with marine foraminifera-bearing shales, indicating a fluctuating shoreline. Still farther north (north of Twp. 72), the Fort Augustus Formation has abundant foraminifera in most of the shaly strata and is probably mainly marine in origin (Mellon, 1967).

C. THE SOUTHERN AREA

The three-fold subdivision of the Mannville Group as defined by Williams (1963) or the six-member Mannville Formation of Nauss (1945) cannot be extended into the southern portion of the study area. The Lower Mannville and the lower part of the Upper Mannville disappear eastward into the area where the Cantuar Formation (Price, 1963; Maycock, 1967) is recognized. This pinching out results in part from the fact that the pre-Mannville surface rises towards the east.

The Cantuar Formation was established by Price (1963) for the basal Lower Cretaceous sediments in southern Saskatchewan, and the Pense Formation for the strata between the Cantuar Formation and the

overlying Joli Fou shale. The Pense and the Cantuar together form the "basal Cretaceous sandy group" of Price (1963, p. 5). South of the Mississippian erosional edge (i.e., south of Twp. 35) in the study area, Maycock (1967, p. 13) used the term "Continental Facies" in lieu of Cantuar Formation and north of the erosional edge, correlative sediments were referred to as "Undifferentiated Mannville Group". Since the Pense Formation cannot be recognized within the study area (see also Maycock, 1967, figure 12) the writer has adopted Maycock's terminology, "Undifferentiated Mannville Group", to describe the Mannville beds in the southern part of the study area. The Undifferentiated Mannville Group and the Continental Facies have very similar lithology (Maycock, 1967, p. 20) and the following description is applicable to both.

Maycock (1967) described his Continental Facies as "extremely heterogeneous" and consisting of lithic sandstones associated with argillaceous siltstone, sandstone of variable clay content, lignite, carbonaceous shales and mudstone, together with minor rocks rich in carbon filaments. The lithic sandstone he described exhibits calcitic replacement of the matrix and has relatively simple mineralogy, with the main components, in order of importance, being quartz, feldspar, chlorite and/or biotite and muscovite. The presence of the less stable minerals indicates relatively rapid transport with little reworking (Maycock, 1967), as does the presence of sedimentary, igneous (volcanic) and metamorphic rock fragments. A western source was suggested.

Approximately one hundred and sixty-feet below the top of the Mannville in the southern part of the study area, a major coal seam occurs. This seam was correlated with seam 8 in the northern part of the area on the basis of its stratigraphic position, using the top

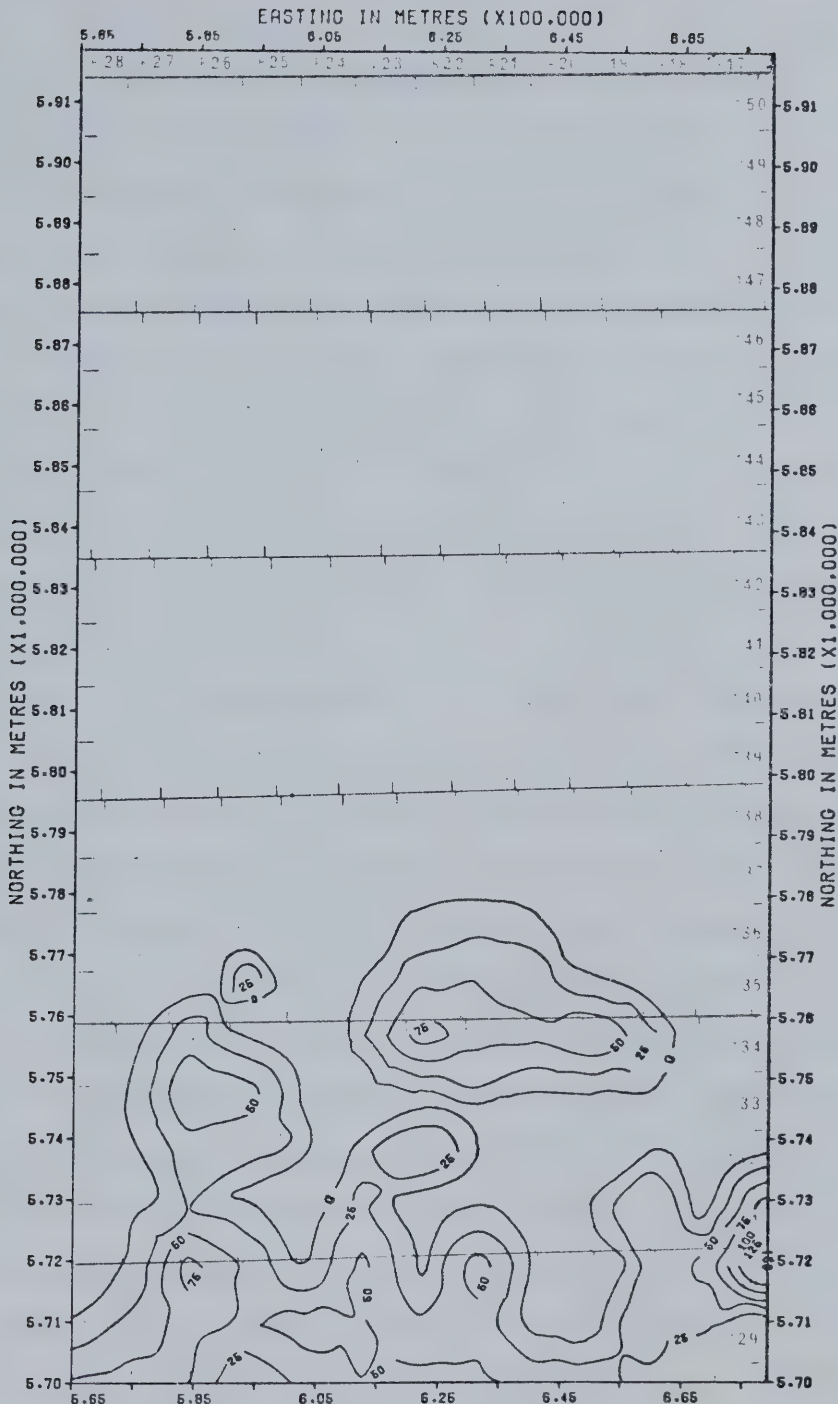
of the Mannville as the datum (figure 4.2). In both areas, the seam shows similar geophysical log characteristics with a relatively high resistivity and a negative SP deflection. Therefore, coal seam 8 at the top of the Borradaile Member in the northern area has its correlative in the south, although it is absent between Townships 36 and 39 (figure 4.6).

In the southern portion of the study area where Mississippian rocks crop out below the Mannville, the Deville Member is the basal unit of the Mannville Group (figure 4.8).

The Pense Formation, together with the underlying Cantuar Formation, forms the "basal Cretaceous sandy group" of Price (1963, p. 26). According to Price and Ball (1971), the Pense Formation is present over most of the northern Williston Basin and has an average thickness of about 150 feet. In the Duval potash shaft (Twp. 36, Rge. 6 W3M), the formation is less than 50 feet thick (Price and Ball, 1971) and thins to zero a short distance to the northwest towards the area of Maycock's (1967) Undifferentiated Mannville Group. In the Duval shaft, the Pense Formation is composed mainly of quartzose sandstone with numerous shale interbeds in the basal third of the interval.

D. SOUTHWESTERN SASKATCHEWAN AND THE STUDY AREA

In southwestern Saskatchewan, Christopher (1974) divided the Mannville Group into the Success, Cantuar and Pense Formations (figure 4.1). The Success Formation is composed of kaolin-indurated quartz sandstone with accessory chert. The Success Formation, plus the basal McCloud Member of the Cantuar Formation, are equivalent to the Lower Mannville of Alberta.



ISOPACH MAP OF THE DEVILLE MEMBER.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 25 FT.

SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

Fig. 4.8

The McCloud Member of the Cantuar Formation is composed "... largely of autochthonous sandstones overlain by an estuarine to marine shale that reaches southward from east-central Alberta to the International Border in Saskatchewan as ria-like fingers of the marine [sic] Ellerslie Formation." (Christopher, 1975, p. 523). It is correlated with the Dina Member and the Cummings shale unit (Christopher, 1974, p. 49).

In the present study area, deposition during McMurray time (Dina Member) as well as during Clearwater time (Cummings Member) was confined to north of Township 40 (figures 4.3 and 4.4). Based on the data available, the writer does not agree with Christopher (1975, text-figure 4) that the Dina Member and the Cummings Member or their equivalents extend further south than Township 40. In this figure, Christopher (1975) shows the McCloud Member, in "valley form", extending southward from the "marine Ellerslie Formation" (Christopher, 1975, p. 523). The present writer could not recognize either the Dina or the Cummings (or their equivalents) on the geophysical logs in areas other than that shown in figures 4.3 and 4.4. Moreover, the "Ellerslie Formation" is probably not of marine origin (Williams, 1963, p. 356).

Maycock (1967, p. 52), on the basis of petrographic similarity between his Continental Facies in southwestern Saskatchewan and the Grand Rapids Formation, concluded that in western Saskatchewan "... the lowest beds in the 'Undifferentiated Mannville Group' are ... most probably Aptian and/or Lower Albian in age and the Continental Facies and Pense Formation Middle Albian". On the other hand, Christopher (1974, p. 50) stated that "The sandstones of the McCloud Member ... in the Tidewater Southey Crown [Lsd 4-29-22-28 W2M] well is [sic] placed in the Barremian, and the superjacent shale (calcareous member) is dated upper

Neocomian, i.e., presumably Upper Barremian. The Dimmock Creek (glauconitic member) is given an Upper Barremian to Albian (?) but possibly Aptian age." However, both writers realized the difficulties in assigning a definite age to the Lower Mannville sediments due to the lack of faunal and/or floral evidence. Unless further work is done in this area, the evidence presented leads the writer to conclude that during the deposition of the McCloud Member and possibly the Dimmock Creek Member in Christopher's study area, deposition of the Undifferentiated Mannville and/or the Continental Facies had not even begun. Therefore, equating the Ellerslie sandstone with the McCloud Member (in "valley form") as shown in Christopher's (1975, text-figure 4) figure appears to be questionable (see also "Interpretation of the Vertical Variability Maps in Chapter 7).

Chapter 5

DEPOSITIONAL ENVIRONMENT OF THE MANNVILLE GROUP

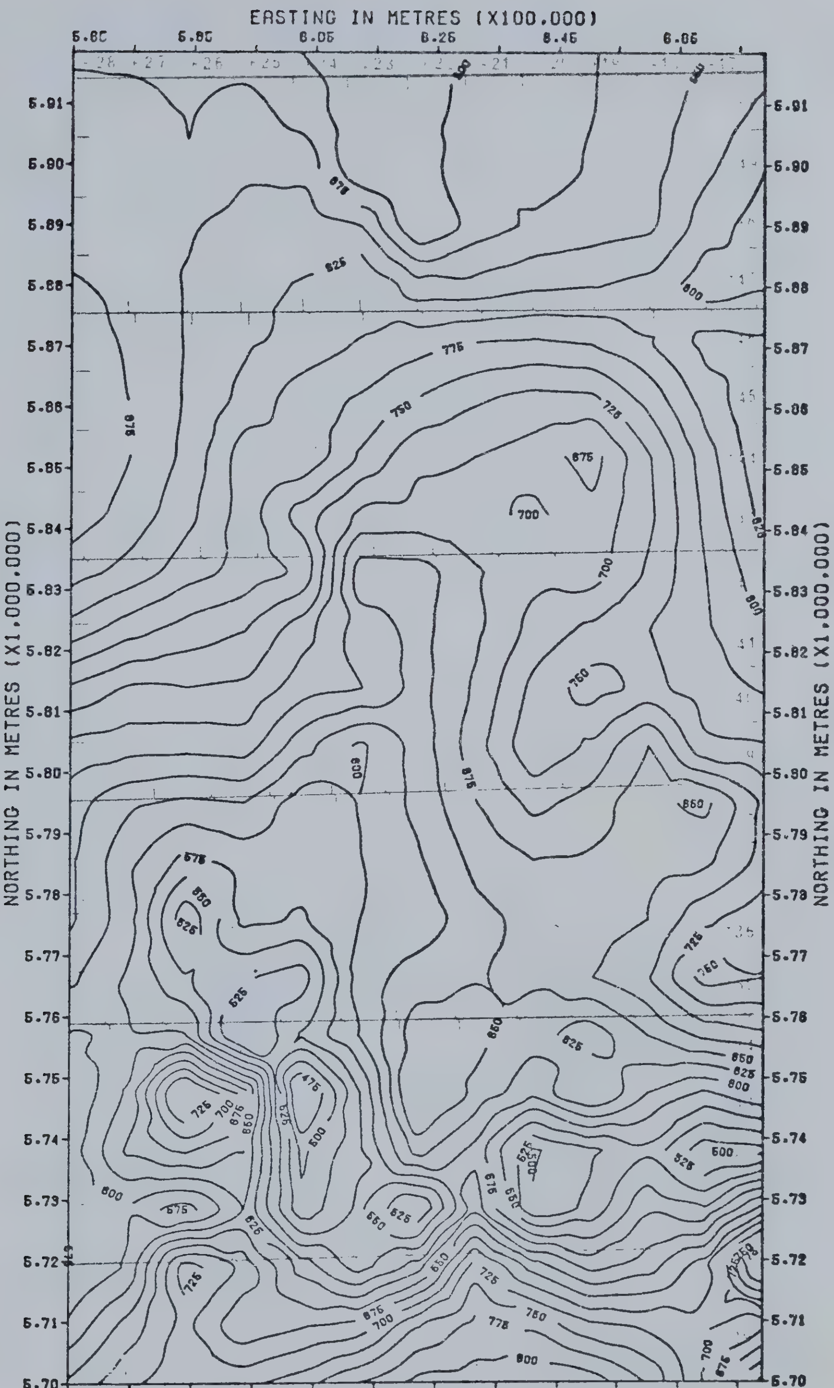
A. INTRODUCTION

A complete regional synopsis of the depositional environments of Cretaceous time has been given by Williams and Stelck (1975) and Jeletzky (1971).

Following a long erosional period during pre-Mannville time, the topography in the study area had a maximum apparent relief of approximately four hundred feet when Mannville deposition began (figure 5.1), being high in the south where the resistant Mississippian rocks cropped out (figure 5.2) and more gentle in the north where Devonian beds were exposed. This apparent relief may be partly due to contemporaneous salt solution of the underlying Devonian evaporite, leading to collapse of the overlying Mannville beds and hence, increases sediment accumulation locally. The term 'apparent relief' is used because salt collapses occurred both syn- and post-deposition of the Mannville sediments. On the basis of the difference in relief, and with the Battleford Arch (approximately Twp. 40) as a dividing line (see discussion below), the area can be divided into northern and southern portions for discussion purposes.

B. NORTHERN AREA

The Dina Member was deposited during early Cretaceous (Aptian to Early Albian) time. The source of the member was suggested by Nauss (1945, p. 1614) as possibly being from the underlying Devonian lime-

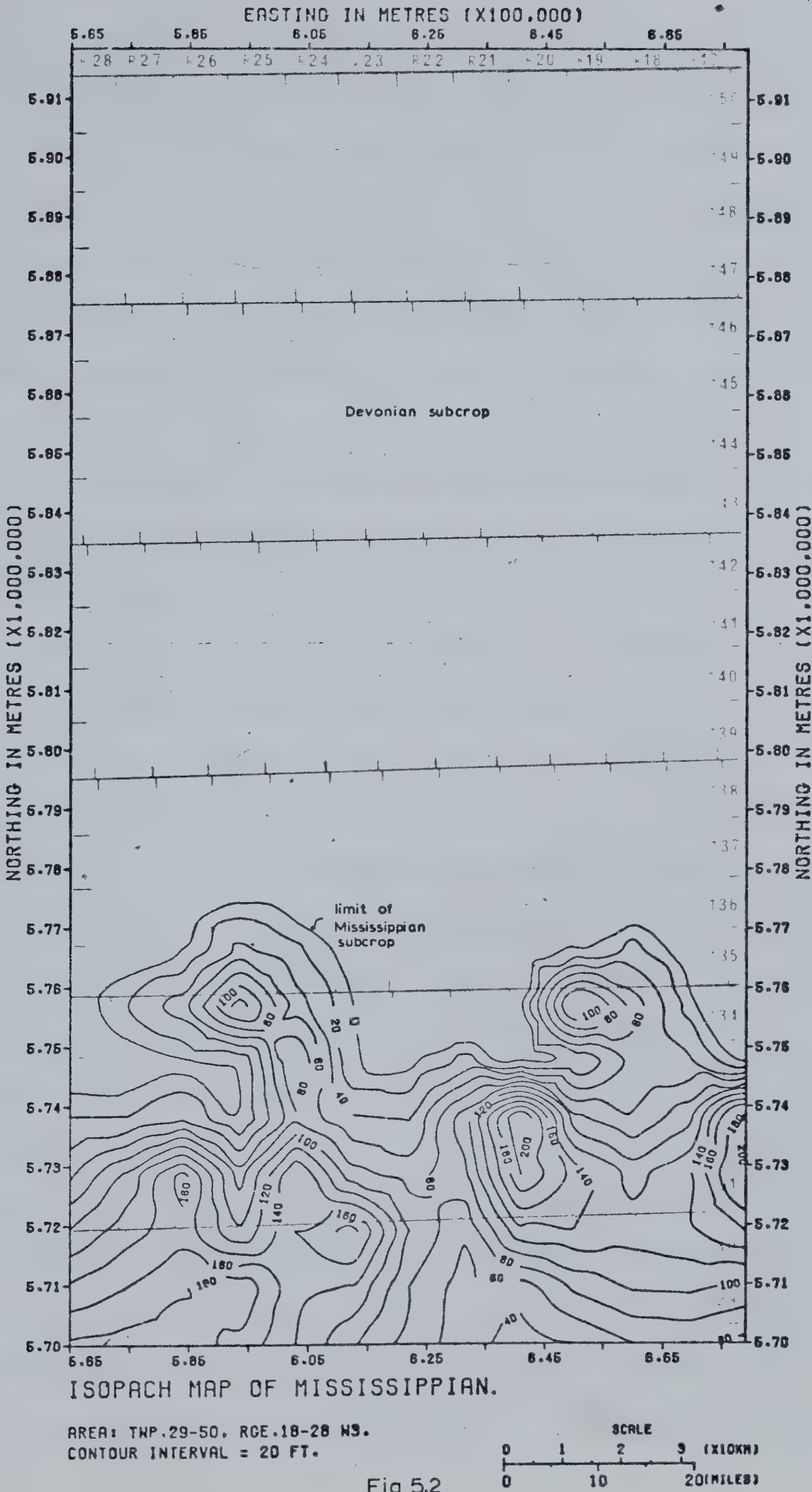


ISOPACH MAP:BASE OF FISH SCALES TO BASE OF MANNVILLE.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 25 FT.

SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

Fig.5.1



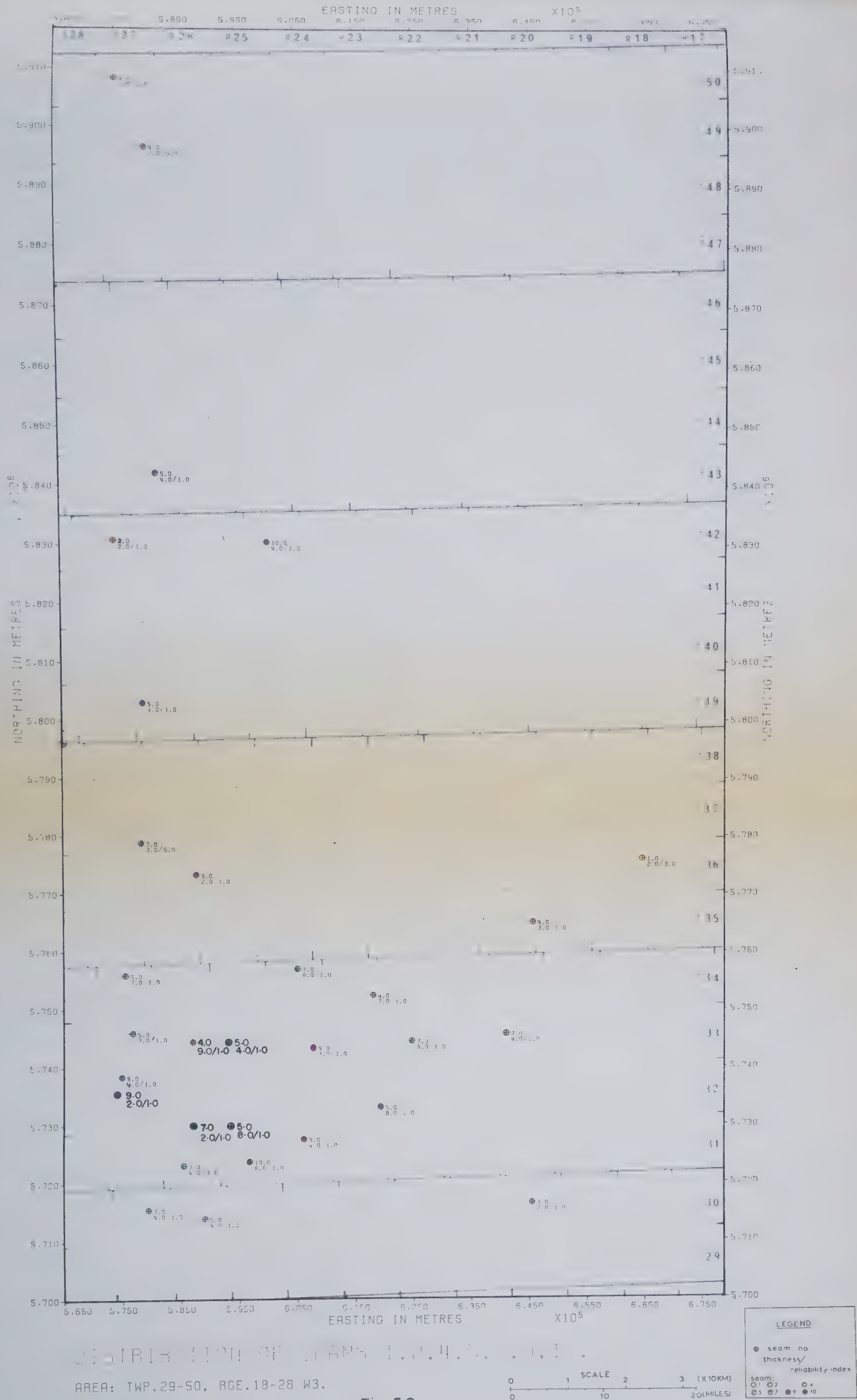
ISOPACH MAP OF MISSISSIPPIAN.

AREA: TWP.29-50, RGE.18-28 W3.
CONTOUR INTERVAL = 20 FT.

Fig. 5.2

stone. However, in central Alberta, the corresponding McMurray Formation has a Precambrian source (Williams et al., 1962). The Dina Member filled in the topographic lows, reducing the topographic relief before the transgression of the Clearwater Sea in which the Cummings Member was deposited. The Battleford Arch set the southern limit for the Clearwater Sea and therefore the Cummings Member. Within the study area, both Dina and Cummings are sand and together they subdued the relief further. Seam 3 was deposited near the top of the Cummings indicating a temporary emergence at that time. Westward toward the trough in central Alberta, the Clearwater Sea transgressed approximately to the present vicinity of Calgary (Williams and Stelck, 1975, text-figure 2) and stayed much longer than in the northeast.

No attempt has been made to subdivide the rest of the Mannville Group into individual members. It suffices to say here that north of the Battleford Arch, post-Cummings deposition was mainly continental, as was the case in the Vermilion area to the west (Nauss, 1945). The lack of seams 4, 5, 6 and 7 in the northeast (figures 5.3a and b) was probably due to non-deposition. Seam 8 occurs at the top of the Borradaile Member ("Sparky" sand in oil industry terminology). According to Nauss (1945), the Borradaile is a near shore, marine-reworked sand and the overlying O'Sullivan Member is a deltaic sand in the area to the west. Therefore, seam 8 represents the emergence of the Borradaile Member with development of widespread swampy conditions (see figure 4.6). No younger seams were found in the area (seams 9 and 10 are of very local extent in the south). The absence of coal in the O'Sullivan Member is probably due to the increase in sediment supply, leading to



AREA: TWP.29-50, RGE.18-28 W3.

Fig. 5.3a

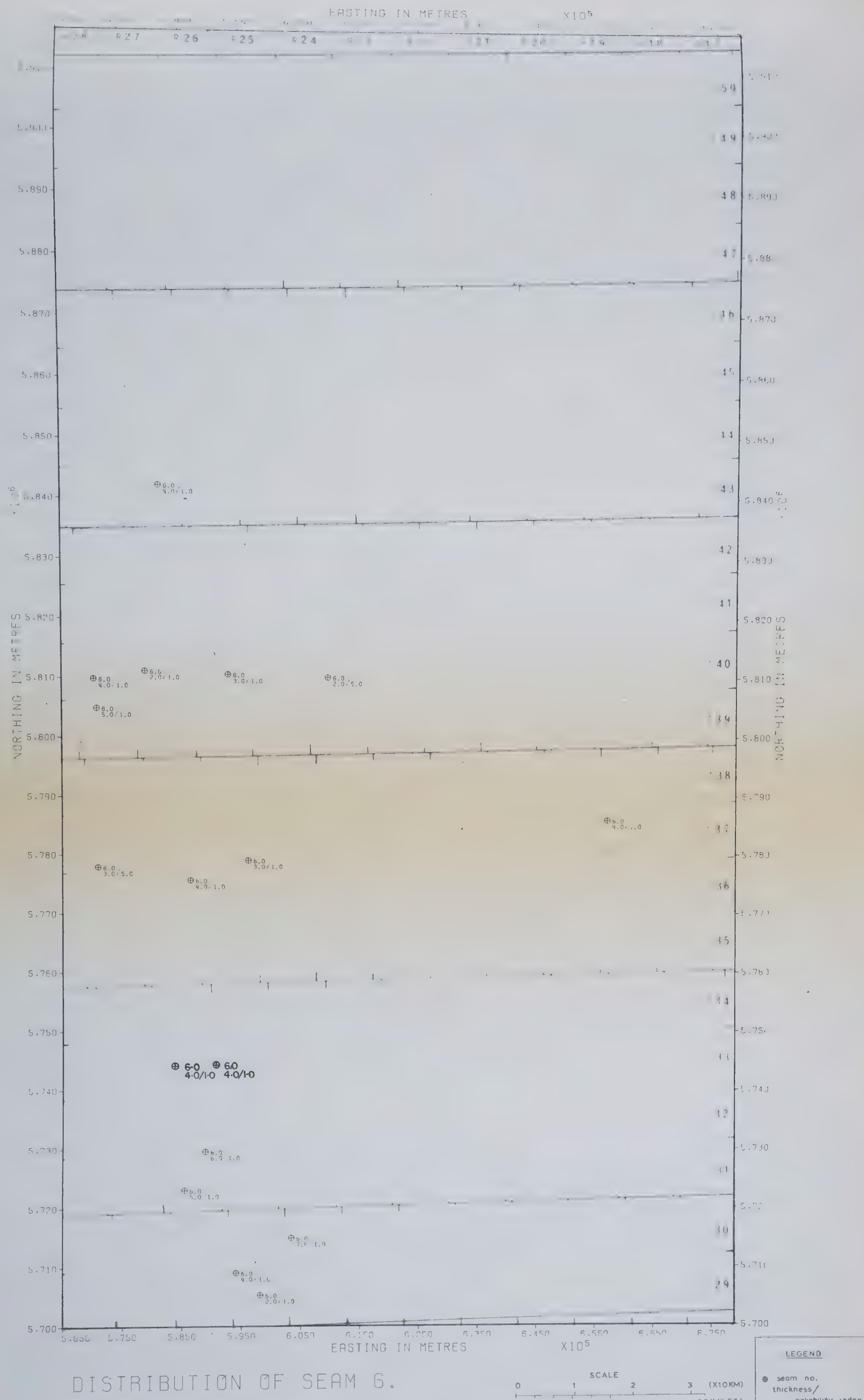

EASTING IN METRES
X10⁵
NORTHING IN METRES
DISTRIBUTION OF SEAM 6.
SCALE
(X10KM)
20(MILES)
LEGEND
seam no.
thickness/
reliability index

Fig. 5.3b

non-swampy dry continental environments. At the end of O'Sullivan time, however, the rate of subsidence must have increased, leading to the invasion of the late Early Cretaceous sea and the deposition of the Joli Fou Shale which ended the history of the Mannville Group.

C. SOUTHERN AREA

South of the Battleford Arch, depositional environments during Mannville time were different from those farther north. In this area, the entire Mannville Group is of continental origin and contains ten coal seams each of limited areal extent scattered vertically throughout it (figure 5.3). Price et al. (1971, p. 20) described the distribution of coal in the Cantuar Formation as follows:

> "The thickest coal bed occurs in strata considered to be river channel and intertidal sediments and not in typical 'coal measures'. Channel filling and the rounding of some wood fragments suggest that this 'coal' has accumulated from transported wood such as that found in log jams along river banks or collections of driftwood in shallow bays and not from the classically conceived mat of swampy vegetation."

This drift origin may explain the erratic distribution of the coal seams in the study area which is reflected in figure 5.3a.

In describing the Cantuar Formation in east-central Saskatchewan, Price et al. (1971, p. 19) noted that "... the formation is distinguishable eastward as far as the Manitoba Escarpment and well into the southern part of the Williston Basin. Northwestward, towards the region of North Battleford [Township 43], the beds are included in the Mannville Group", thus suggesting a facies change in the vicinity of Township 43.

Lower Cretaceous sedimentation in the south began with the deposition of the Deville Member. According to Christopher (1974, p. 104), the base level of the Deville basins were higher than the levels of the master streams and hence, the basins formed an internal drainage system. It was this centripetal drainage system that eroded the Mississippian rocks and produced the cherty Deville Member. South of the Deville basins, the Swift Current Platform sloped gently to the south where the Success Formation was deposited. Deposition of the Cantuar Formation proper was brought about by uplift of the northern flank of the Swift Current Platform in the vicinity of Township 23 (Christopher, 1974, p. 104, figure 45), bringing the base level of the master streams higher than that of the Deville basins. Consequently, the drainage system turned to the north, breaching the Deville basins and the Mississippian outcrops at several places. On the Devonian strata to the north, the streams joined a master stream of subsequent valleys opening west-northwesterly into Alberta, where they join similar valleys, such as the 'St. Paul Channel' mapped by Williams (1963). Within the study area, subsidence and deposition were probably in equilibrium, resulting in a low lying alluvial plain where streams flowed slowly northwestward, emptying into the east-central Alberta Plains (see Nauss, 1945, p. 1627) and depositing their load as deltas and related features. On the alluvial plain, coal was deposited.

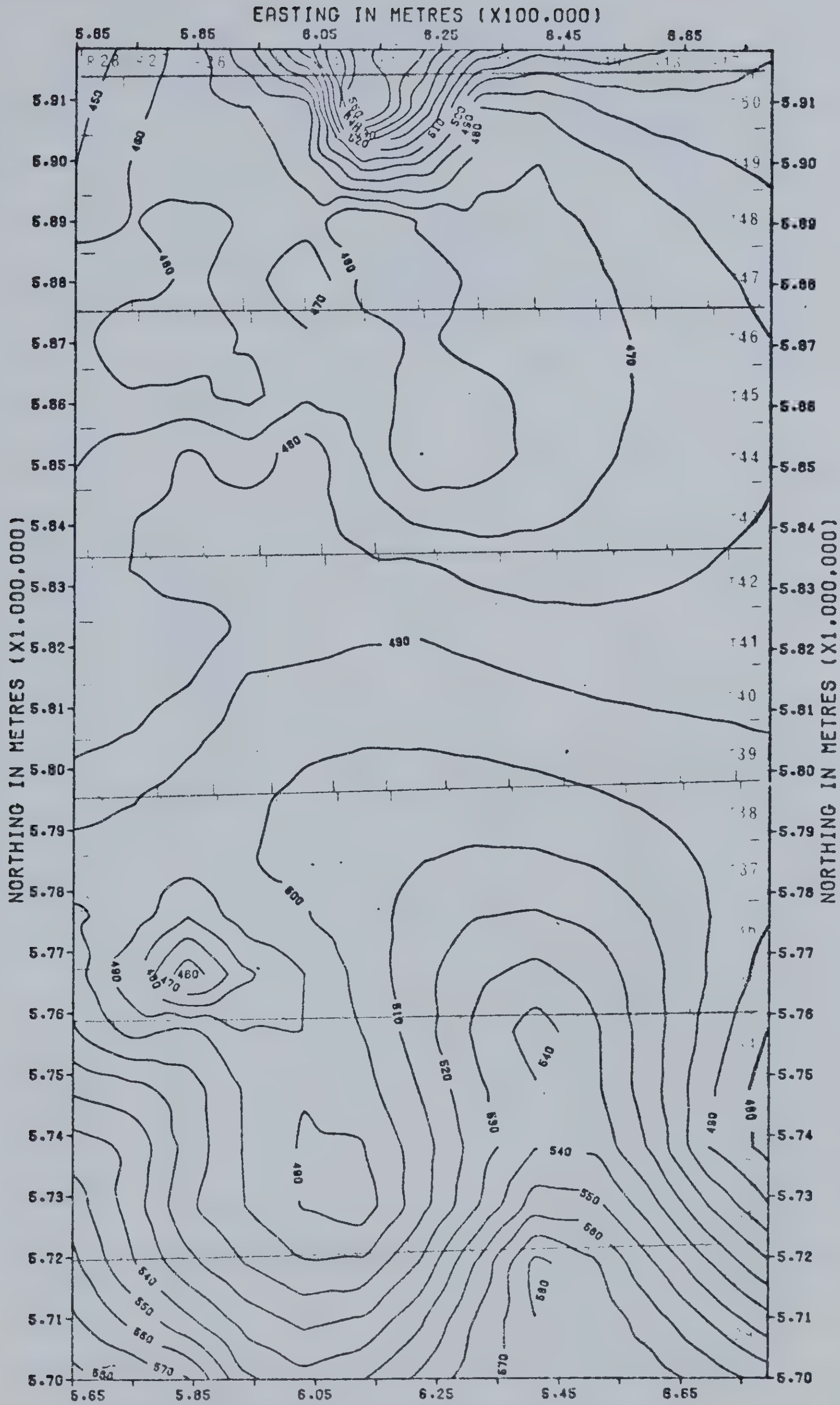
The major seam in the southern portion of the study area is seam 8, which, however, is absent from Townships 37 to 39. In view of the uniform thickness of the Mannville sediments overlying seam 8 (figure 4.2) and the fact that no unconformity was detected at the base of

these sediments, the writer speculates that the absence of seam 8 was due to non-deposition.

Deposition of the Cantuar Formation in the south (approximately south of Twp. 32) was brought to a close by the shallow marine transgression which produced the sands of the Pense Formation. Within the present study area, the Undifferentiated Mannville Group (equivalent to the Cantuar Formation) is overlain by the late Lower Cretaceous Joli Fou Formation.

In general, central Saskatchewan, during Lower Cretaceous time, was high. In the northern portion of the study area (north of Twp. 40), near shore and deltaic environments alternated through Mannville time. In western Saskatchewan (from approximately Rge. 24 to 28 W3M) along the provincial border, a fluvial plain environment dominated the area (Maycock, 1967), where coal seams were deposited (figures 5.3a and b). Across the border to the west the McMurray and the Grand Rapids Formations were deposited in fluvial and deltaic environments while the median Clearwater Formation is a marine shale. The eastern part of the map area remained above sea level most of the time with occasional marine transgressive tongues and sparse coal deposition.

After the deposition of seam 8, the resulting topography was considerably subdued, with an apparent relief of about 110 feet (figure 5.4). The absence of seam 8 in Townships 37-39 is due to non-deposition. Uniform deposition continued thereafter until the end of Mannville time. The top of the Mannville shows an apparent relief of 180 feet (figure 5.5) as compared with 425 feet in the sub-Cretaceous erosional surface (figure 5.1).

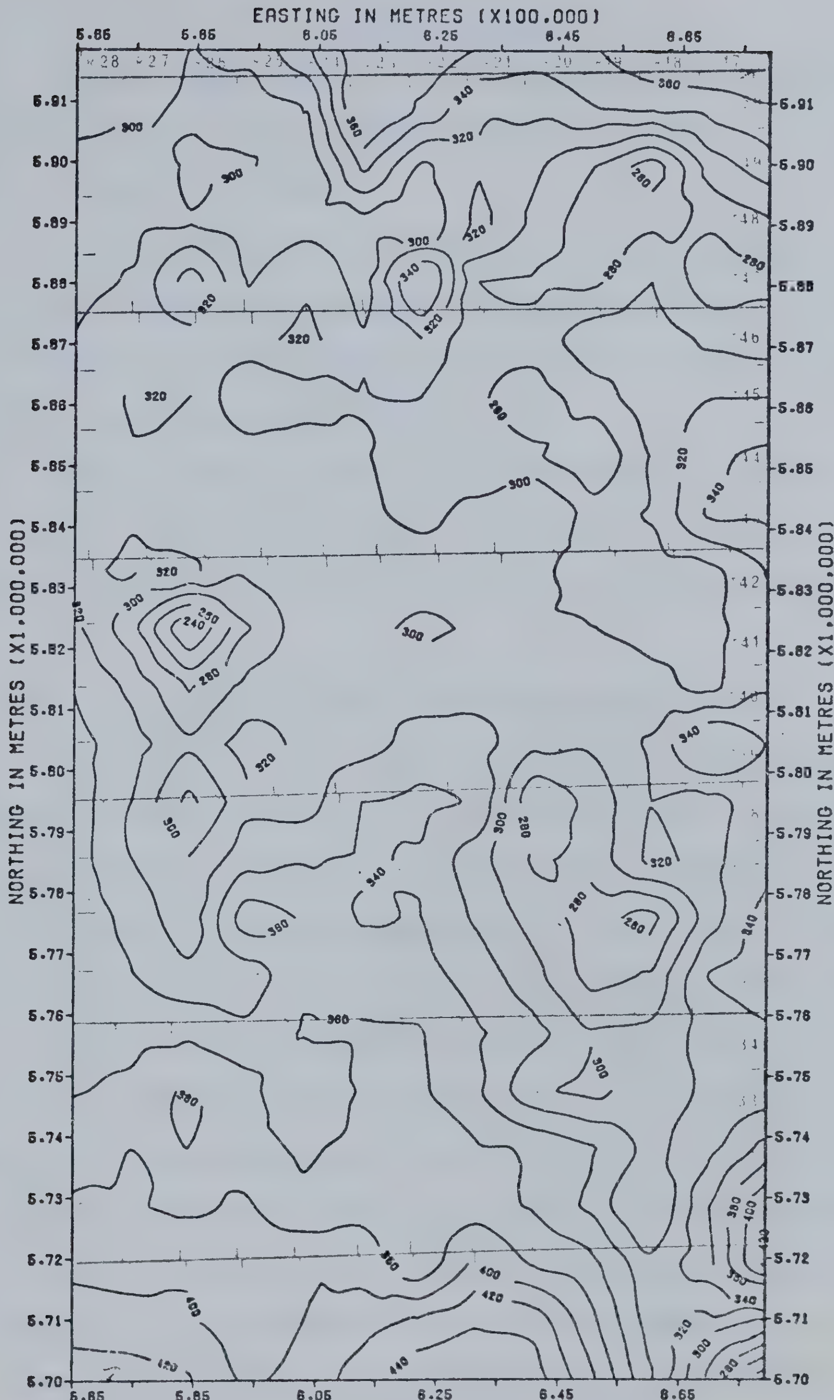


ISOPACH MAP: BASE OF FISH SCALES TO SEAM 8.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 10 FT.

SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

Fig.5.4



ISOPACH MAP:BASE OF FISH SCALES TO TOP OF MANNVILLE.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 20 FT.

SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

Fig. 5.5

D. SPECIAL FEATURES

From the descriptions of the stratigraphy and the depositional environments, three special features stand out clearly within the study area. They are as follows:

(1) the southern limit of both the Dina and the Cummings Members is in the vicinity of Township 40 and trends approximately east-west, whereas the equivalent McMurray and Clearwater Formations in central Alberta extend much farther south;

(2) the absence of seam 8 between Townships 37 and 39;

(3) the completely different depositional environments between the northern (north of Twp. 40) and the southern parts of the area.

E. THE BATTLEFORD ARCH AND THE MANNVILLE GROUP

The Battleford Arch in central Saskatchewan is the northeastern extention of the Sweetgrass Arch in southern Alberta. In his discussion of basement control of Cretaceous sand sequences in western Canada, Stelck (1975) has shown the distribution of Precambrian basement features (figure 5.6). During earliest Cretaceous (Neocomian) time, marine sediments (Monteith, Beattie Peaks and Monach Formations) were confined to the Keg River Low north of the Peace River Arch. South of the arch, deposition of the Blairmore Group did not start until Aptian time, and in the West Alberta Basin, the Blairmore lies unconformably on Jurassic or older strata. The basal conglomerate (Cadomin Formation) of the Blairmore Formation only exists in the Foothills area and is absent under the Plains. The Peace River Arch apparently was an area of erosion (see Stelck, 1975, p. 432, text-figure 4). In mid-Albian

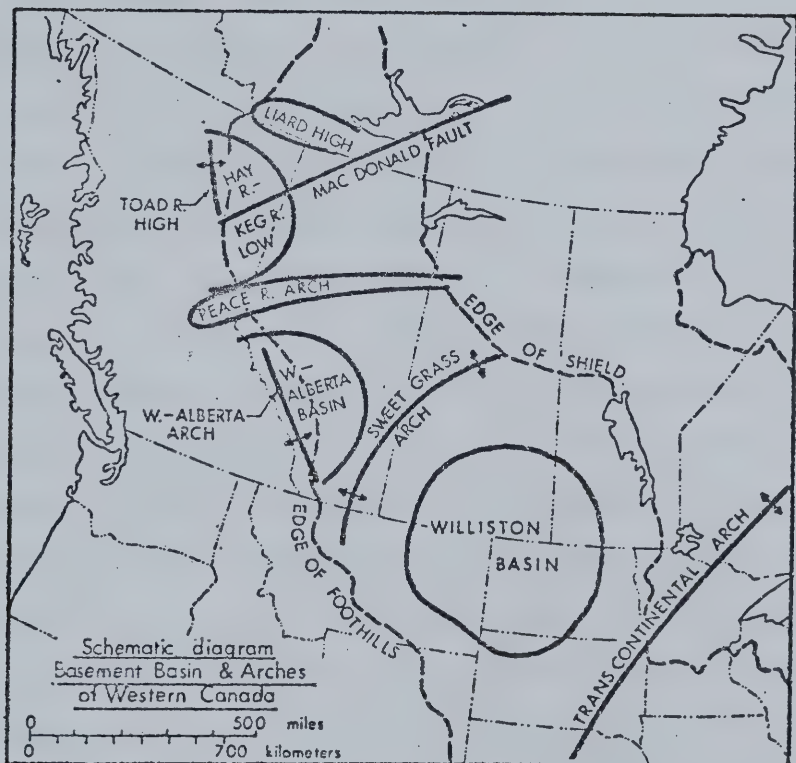


Fig 5.6 SCHEMATIC DIAGRAM of PRECAMBRIAN BASMENT FEATURES of WESTERN CANADA.*

(* after Stelck, 1975)

time, the arch became a demarcation line for facies change; continental and near shore deposits in the south gave way to marine facies in the north.

A similar situation occurred in the present study area. Deposition of the Dina Member began during Aptian time and its distribution was confined to the area north of Township 40. Both in the study area and in Nauss' (1945) area, the member has a sandy lithology and thickens towards the north. After deposition of the Dina Member, the Clearwater Sea deposited the Cummings shale in east-central Alberta and sand in the study area. Like the Dina Member, the Cummings does not extend farther south than Township 40. Therefore, deposition during Aptian to Early Albian time was confined to the north of the study area. The barrier that limited the southern extension of the two members is attributed by the writer to the presence of the Battleford Arch.

Deposition of the continental Cantuar Formation in the southern part of the study area did not start until late Clearwater time when the sea regressed to the north. The overlying Islay, Tovell and Borradaile Members are beach, deltaic and reworked beach sand deposits respectively, whereas the Cantuar Formation remained continental. This difference in facies change, though not as striking as in the Peace River Arch example, is significant enough to indicate the presence of a demarcation barrier. Coal seam 8 ("Wainwright coal", Wilson, 1947) at the top of the Borradaile Member is absent between Townships 37 and 39 due to non-deposition, a fact which also suggests a high in this vicinity which can be attributed to the presence of the Battleford Arch (figure 4.2).

As stated by Stelck (1975), basement control over the deposition of Lower Cretaceous sand is subtle. The Battleford Arch was high during the deposition of the Mannville Group in the study area and controlled the distribution of the Dina and Cummings Members and seam 8.

Chapter 6

STRUCTURAL GEOLOGY

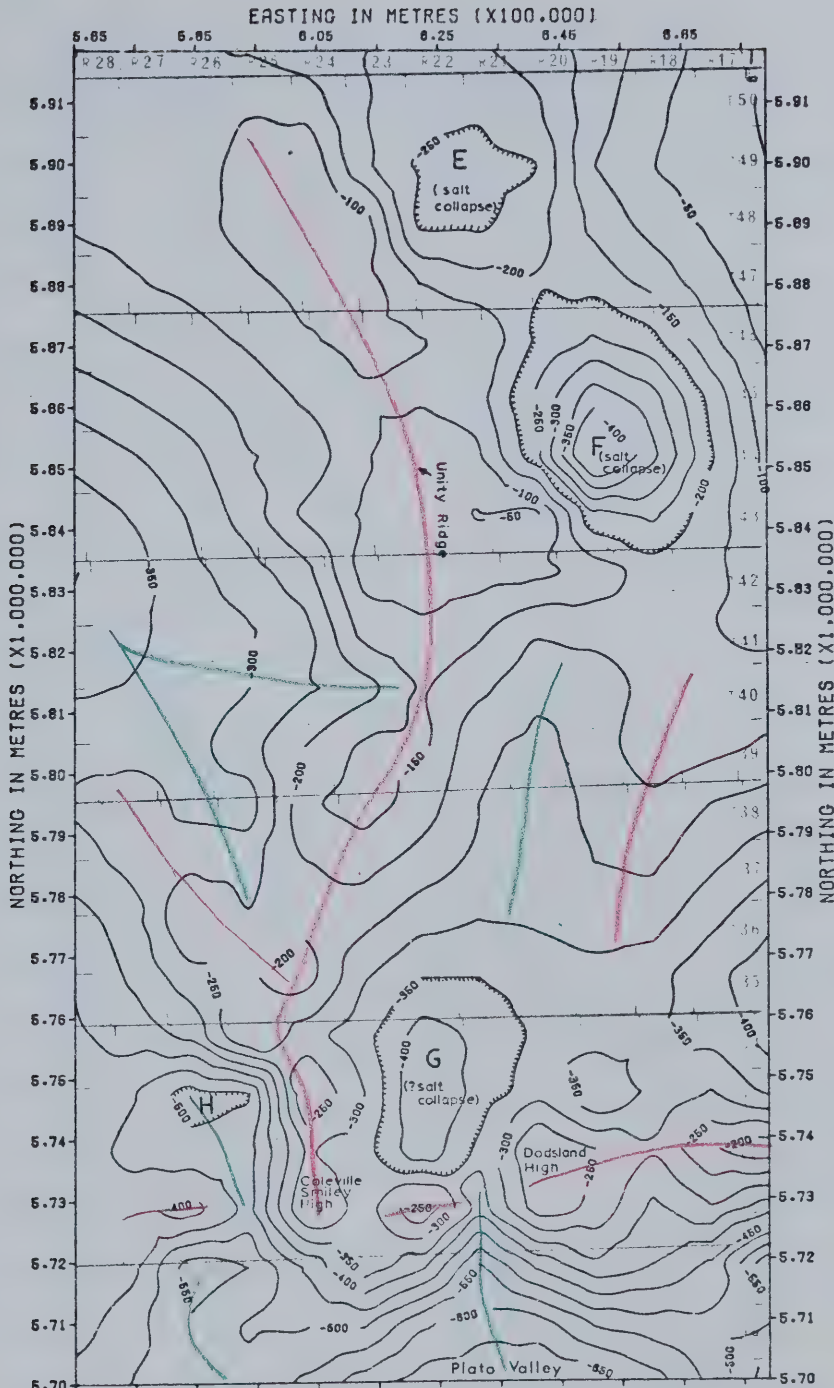
The structure of the Mannville Group, summarized on figures 6.1, 6.2 and 6.4, essentially reflects the topography of the underlying sub-Cretaceous erosional surface.

Figure 6.1 shows the present configuration of the sub-Cretaceous surface. The major dominant feature is the sinusoidal positive feature, named here as the Unity Ridge. Other ridges and valleys run subparallel to this main ridge. These topographic high and low features of the land surface are the results of erosional effect.

Remnants of the Mississippian rocks create east-west trending ridges in the south (Maycock, 1967, p. 55). The south-trending valley in the south of the map area is probably one of the northern arms of the Plato Valley named by Christopher (1975, text-figure 4).

Structure on the top of the Mannville (figure 6.2) is different from that of the base. The sinusoidal Unity Ridge may be seen in the north only, reflected in two offset positive features. Since no major fault was found in the area, the offset is probably a depositional feature and not tectonic. An indistinct, north-trending nose is present in the southeast corner of the map. In general, the features which are very distinct in figure 6.1, are covered up by the Mannville sediments and only the barest outlines remain. The surface has acquired a much more uniform southwesterly dip.

Depressions E and F in the northeast corner of the area show persistent closure of up to 250 feet through the entire Lower Cretaceous



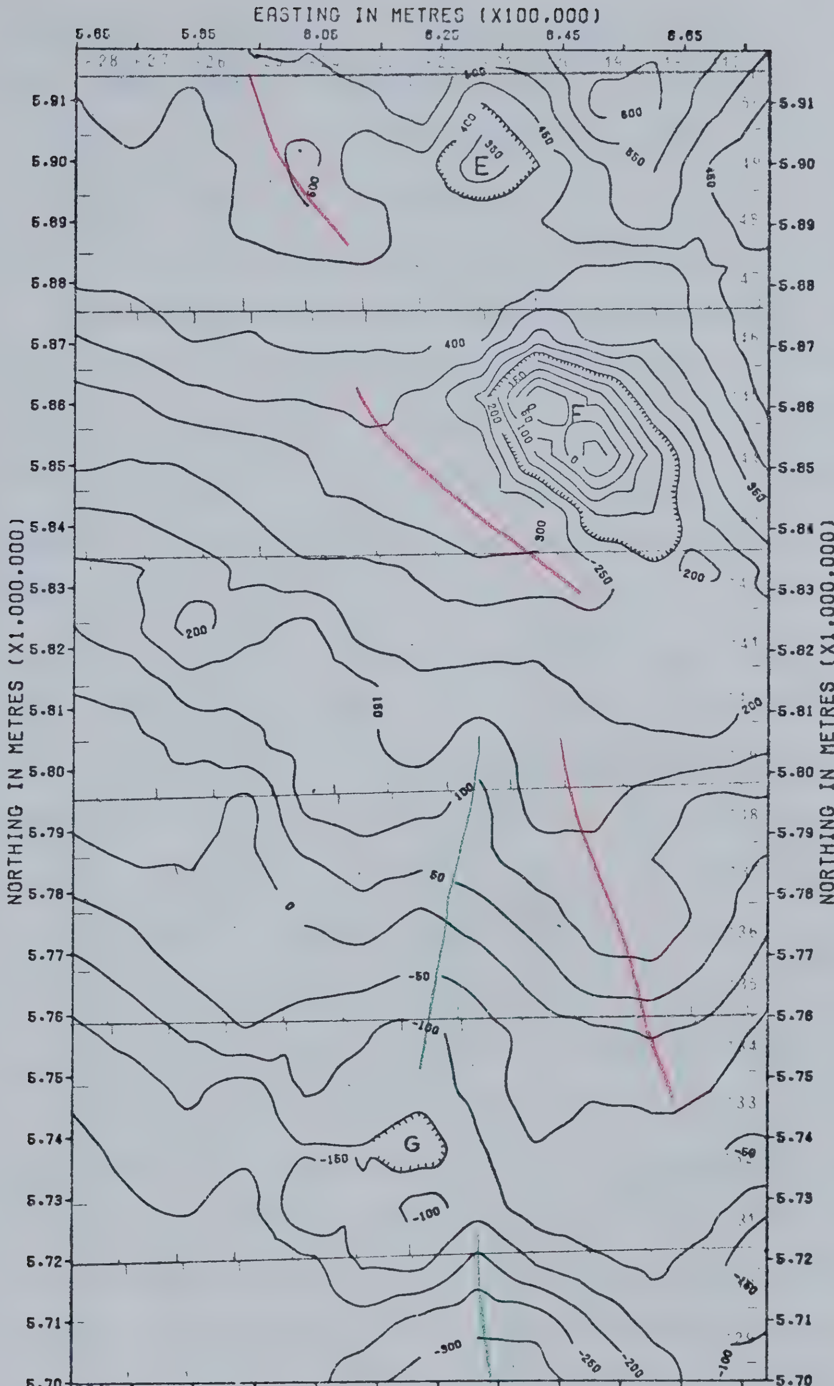
STRUCTURAL MAP OF THE BASE OF MANNVILLE.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 50 FT.
DATUM : MEAN SEA LEVEL.

Fig. 6.1

SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

LEGEND
depression
ridge
valley



STRUCTURAL MAP OF THE TOP OF MANNVILLE.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 50 FT.
DATUM : MEAN SEA LEVEL.

SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

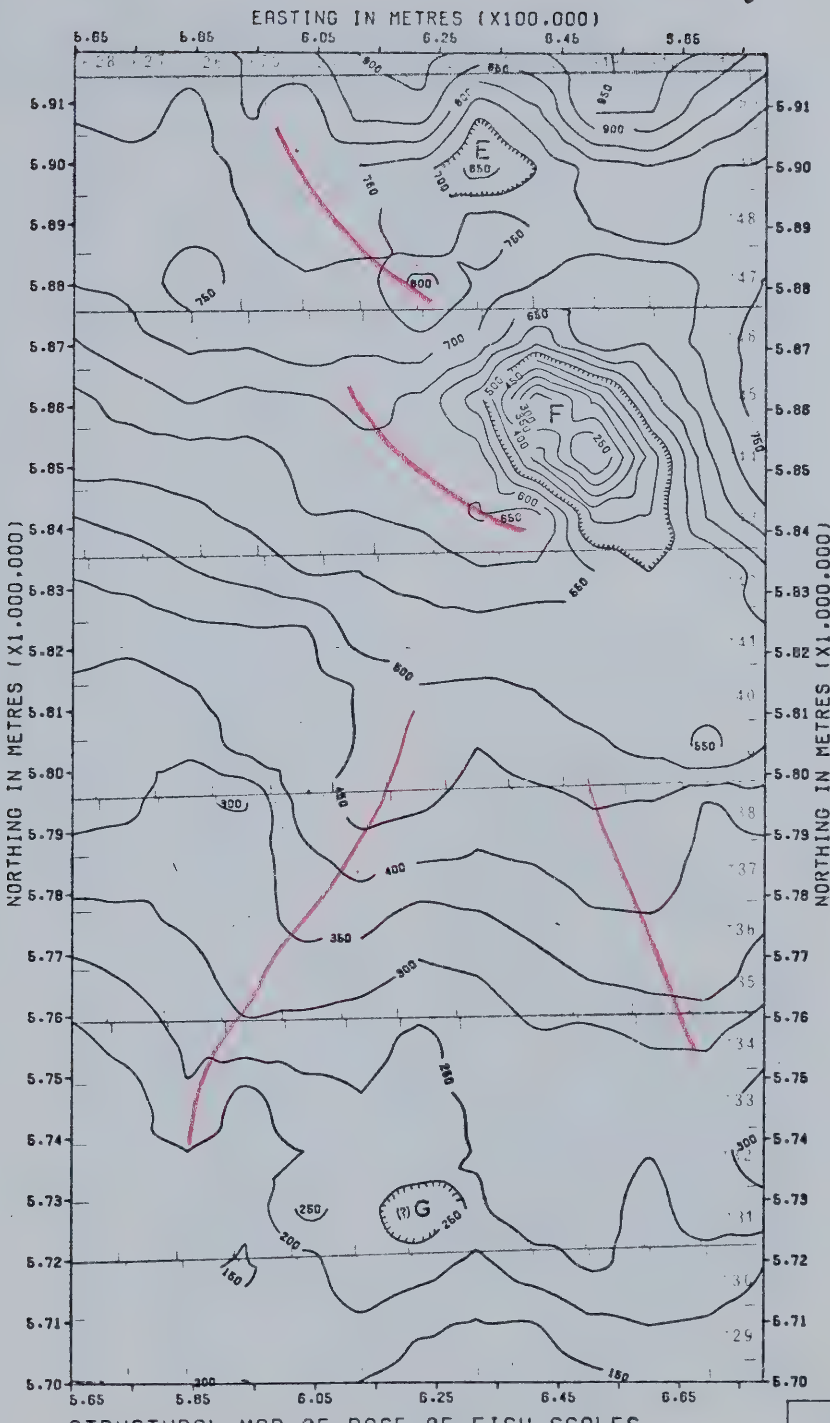
LEGEND
depression
ridge
valley

Fig. 6.2

(figures 6.1, 6.2 and 6.3). They developed in post-Early Cretaceous time since isopach maps of the Mannville Group (figure 6.4) and from the Base of Fish Scales to the top of the Mannville (figure 5.5) do not show any thickening in that area. The depressions are attributed to the collapse of overlying strata due to the removal of underlying Devonian salt.

Depression G in the south of the map area decreased in areal extent through Mannville time and it persisted to at least the end of Early Cretaceous (figure 6.3). Its relief at the base of the Mannville (figure 6.1) is approximately 50 feet. The isopach map of the Mannville Group (figure 6.4) shows only a 25-foot thickening in the same general area, indicating salt collapse started during Mannville time and continued through the Early Cretaceous. Similarly, depression H has a small areal extent with a relief of less than 50 feet at the base of the Mannville (figure 6.1). The isopach map of the Mannville Group (figure 6.4) also shows less than 50 feet of thickening of the sediments in the same area. Syn-depositional salt collapse was the origin of this depression which was filled in during Mannville time so that it does not show up in the structural map of the top of the Mannville (figure 6.2).

The structural section in figure 6.5 shows the regional southerly tilt of the map area, compared with the stratigraphic section (figure 4.2). In discussing the intermediate structures in south-central Alberta, Robinson _et al_. (1969, p. 2367) noted that "... the intermediate structures of the Cretaceous surfaces probably resulted not from differential compaction but from tectonic movements that continued throughout the Cretaceous and possibly into Early Tertiary". This may also have been the case in west-central Saskatchewan.



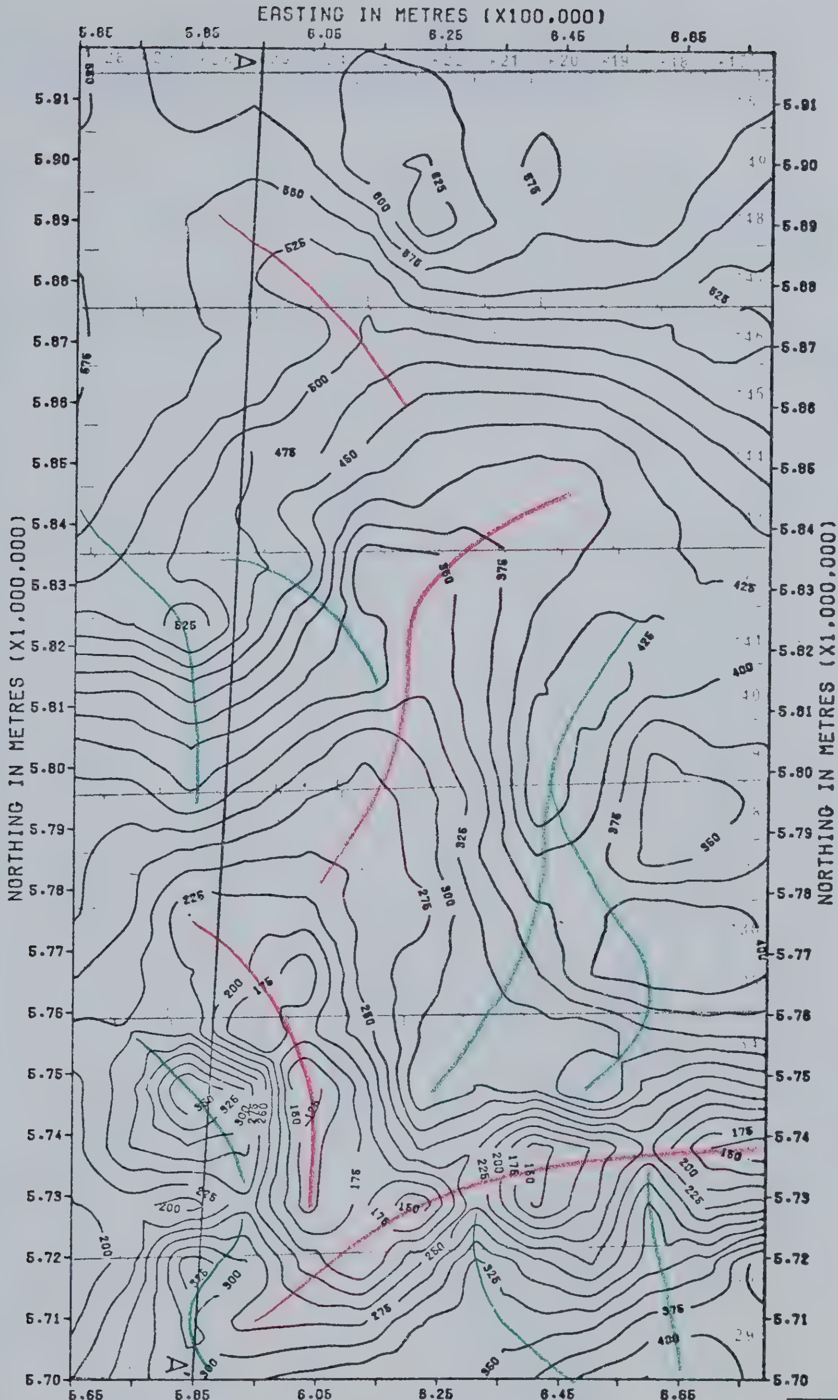
STRUCTURAL MAP OF BASE OF FISH SCALES.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 50 FT.
DATUM : MEAN SEA LEVEL.

Fig. 6.3

SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

LEGEND
depression
ridge
valley



ISOPACH MAP OF THE MANNVILLE GROUP.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 25 FT.

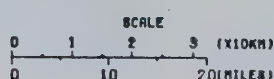
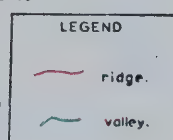


Fig. 6.4



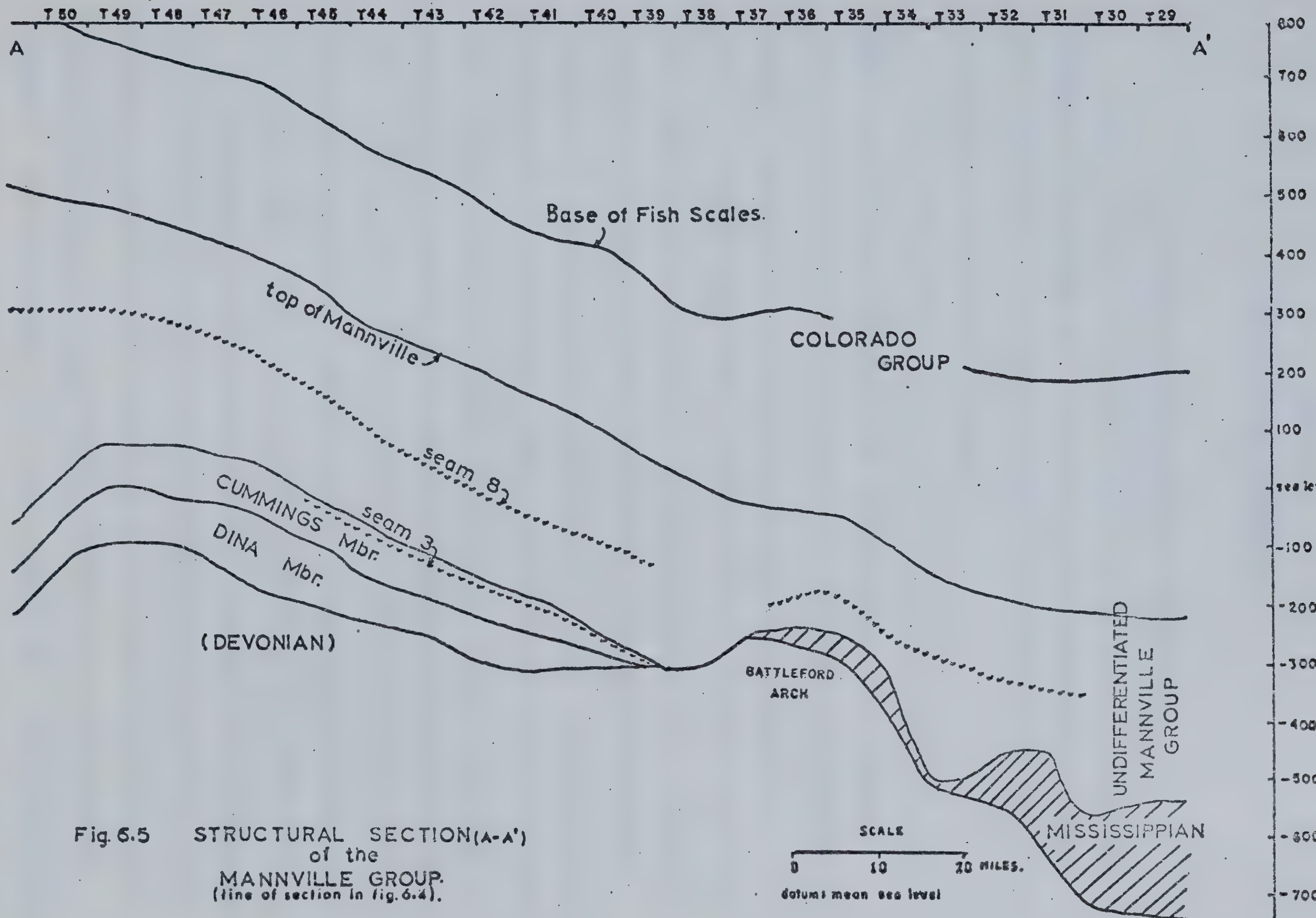


Fig. 6.5 STRUCTURAL SECTION (A-A') of the MANNVILLE GROUP.
(line of section in fig. 6.4).

Chapter 7

COAL RESOURCE ESTIMATION

A. FACTORS AFFECTING RESOURCE ESTIMATION

Several factors have a direct effect on the estimate of the coal resources of the study area. These factors are summarized below and the reader should keep them in mind when considering the tonnage of coal arrived at in the estimation process.

Of the 242 townships in the area, 31 contain no logged boreholes. These townships occur mostly in the central part of the study area. Since resource estimation is calculated on a one-well-per-township basis, these 31 townships are automatically excluded from the calculation - that is, contribute zero value. The total coal thickness in each township, plus the areas with no data, are shown in figure 7.1. From the formula for resource estimation (see below), it may be seen that each addition of a one-foot seam per township will increase the estimate by an increment of 40.7 million tons, hence, the lack of data for the 31 townships may well affect the estimate significantly. On the other hand, because of the laterally discontinuous character of the seams (see section D, this chapter), the extrapolation of data from a single well into a zone of influence of a township involves a large degree of uncertainty and therefore more control points would undoubtedly improve the result.

In 53 townships in the northern part of the study area, the deepest available boreholes did not penetrate the entire Mannville Group. Most of these holes were drilled only to the Tovell Member ("Rex sand" in oil industry terminology). As mentioned in the discussion on the stratigraphy of the northern part of the area, a major coal seam (seam 3) occurs

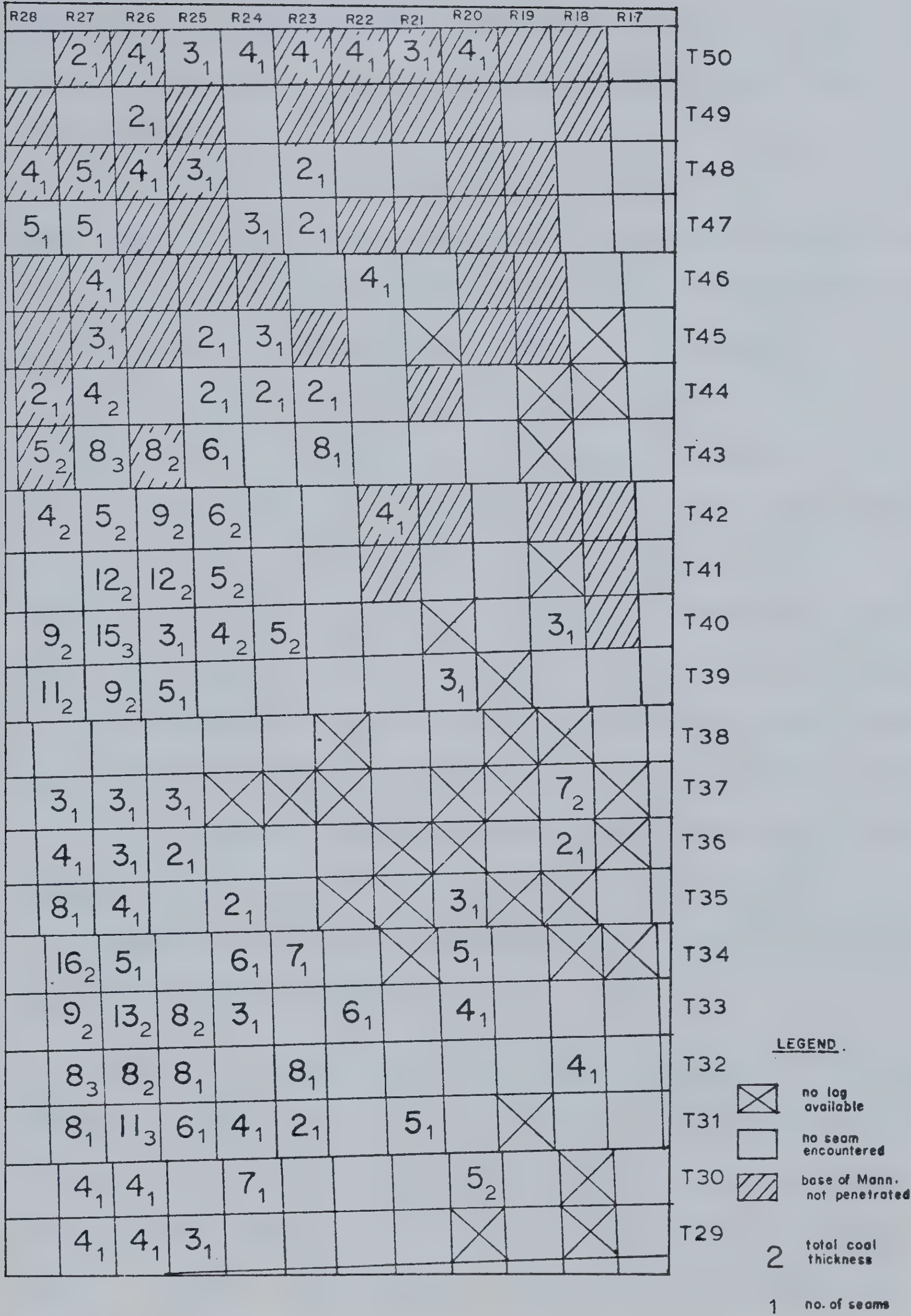


Fig. 7.1 TOTAL COAL THICKNESS DISTRIBUTION.

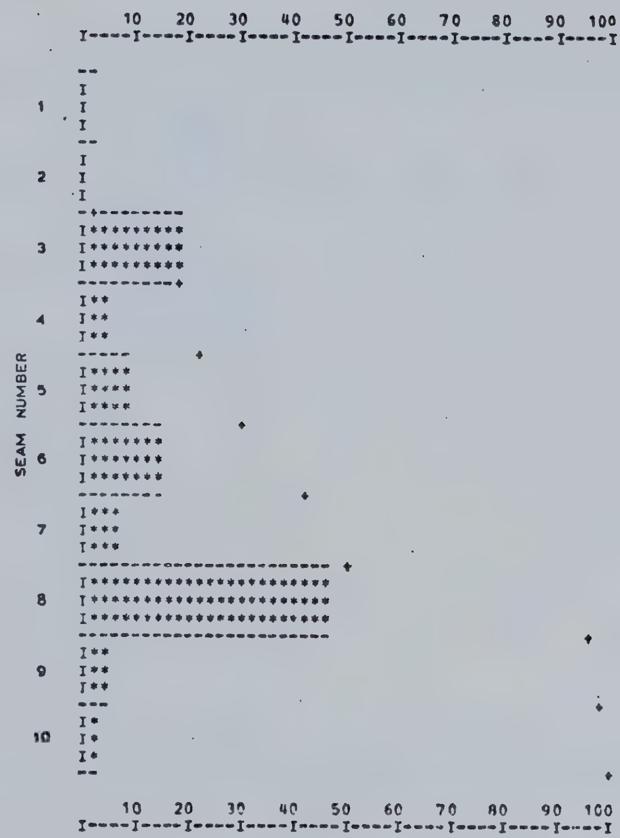
near the top of Cummings Member in the north. Hence, the final estimate is subject to revision should additional data from deeper boreholes become available.

The frequency of seam occurrences is shown in figure 7.2. The two major seams, 3 and 8, were encountered 22 and 59 times, respectively. Seam 6, which underlies the "North Hoosier Basal Blairmore Sand Pool" (White, 1974, p. 128), was found 17 times in the 236 wells.

The geophysical logs used in this study have a resolution of approximately 2 feet and seam thicknesses were read to the nearest foot. However, because of the low resolution of the logs, seams less than 2 feet thick were not identified. In the study area seam thicknesses range from 2 to 9 feet. The mean value is 3.9 feet with a standard deviation of 1.8 feet. Most seams are either 2 feet or 4 feet in thickness (figure 7.3).

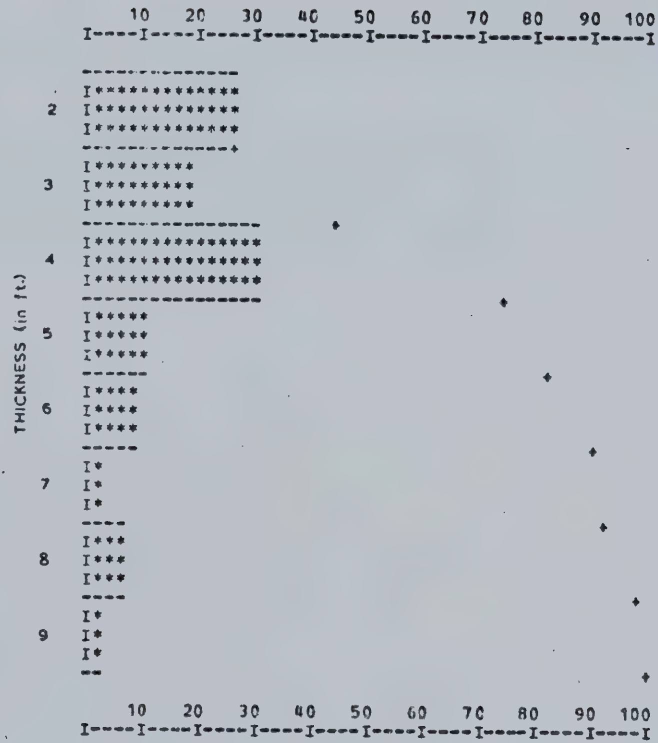
As discussed in Chapter 3, each coal seam as determined from logs was assigned a reliability index of 1, 3 or 5 (also see Yurko, 1976, pp. 11-12). Figure 7.4 shows that 78.1% of the seam identifications were based on a resistivity log and a sonic log (reliability index 1), 18.8% on a resistivity log only (reliability index 5), and 3.1% on resistivity and neutron logs (reliability index 3).

Figure 7.5 shows the total coal thickness map plotted from one hundred and twenty-eight data points including reliability indexes 1, 3 and 5. If only reliability index 1 is used, only one hundred data points are included, but the isopach map shows a very similar pattern. Both maps show a general trend of thickening toward the west of the study area.



FREQ.	REL.FR	CUM.FR	FRACT.
0.0	0.0	0.0	0.0
1.00	0.78	0.78	0.49
1.00	0.78	1.56	1.27
22.00	17.19	18.75	18.42
5.00	3.91	22.66	22.32
9.00	7.03	29.69	29.34
17.00	13.28	42.97	42.59
8.00	6.25	49.22	48.83
59.00	46.09	95.31	94.83
4.00	3.13	98.44	97.95
2.00	1.56	100.00	99.51
FREQ.	REL.FR	CUM.FR	FRACT

Fig 7.2 FREQUENCY PLOT of SEAM OCCURRENCES



FREQ.	REL.FR	CUM.FR	FRACT
0.0	0.0	0.0	0.0
33.00	25.78	25.78	25.44
23.00	17.97	43.75	43.37
38.00	29.69	73.44	73.00
12.00	9.38	82.81	82.36
9.00	7.03	89.84	89.38
3.00	2.34	92.19	91.72
8.00	6.25	98.44	97.95
2.00	1.56	100.00	99.51
FREQ.	REL.FR	CUM.FR	FRACT

Fig 7.3 FREQUENCY PLOT of SEAM THICKNESS

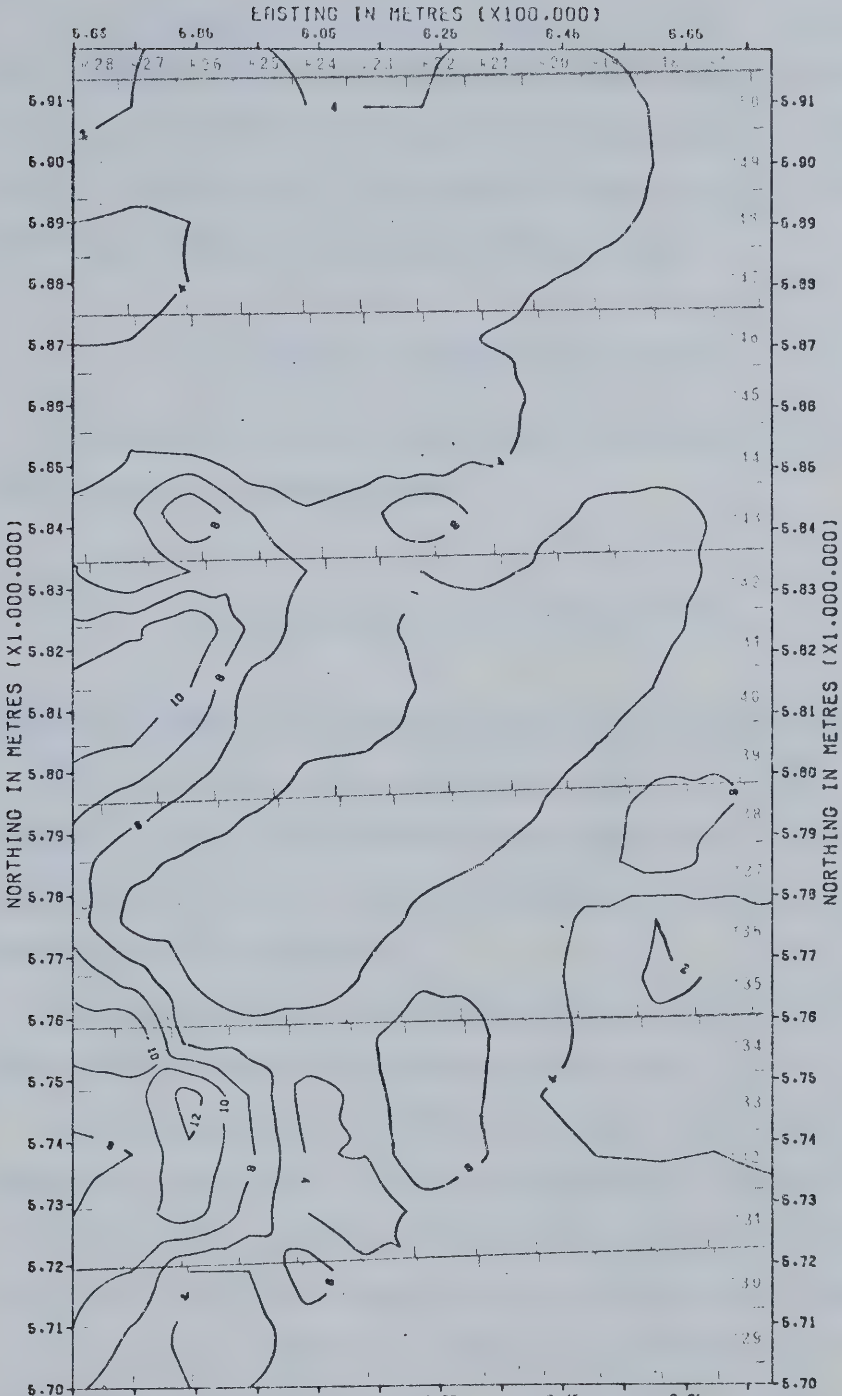
RELIABILITY INDEX

```
        10   20   30   40   50   60   70   80   90  100
      I----I----I----I----I----I----I----I----I----I----I     FREQ.  REL.FR  CUM.FR   FRACT

      ----------------------------------------                   0.0     0.0     0.0     0.0
      I***************************************
 1    I***************************************
      I***************************************
      ----------------------------------------+               100.00   78.13   78.13   77.68
      I
 2    I
      I
      ---                                     +                  0.0     0.0   78.13   77.68
      I**
 3    I**
      I**
      ---                                       +                4.00    3.13   81.25   80.80
      I
 4    I
      I
      ----------                                +                0.0     0.0   81.25   80.80
      I*********
 5    I*********
      I*********
      ----------                                          +     24.00   18.75  100.00   99.51

        10   20   30   40   50   60   70   80   90  100
      I----I----I----I----I----I----I----I----I----I----I     FREQ.  REL.FR  CUM.FR   FRACT
```

Fig 7.4 FREQUENCY PLOT of RELIABILITY INDEX.



TOTAL COAL THICKNESS MAP.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 2 FT.

Fig. 7.5

SCALE
0 1 2 3 (X10KM)
0 10 20 (MILES)

The isopach map of seam 8 is shown in figure 7.6. This map includes fifty-nine data points with reliability indexes 1 (41 data points), 3 (2 data points) and 5 (16 data points). Again, when only reliability indexes 1 and 3 are used, the isopach map shows a similar trend of thickening towards the Saskatchewan-Alberta border.

B. METHODS OF ESTIMATION AND RESULTS

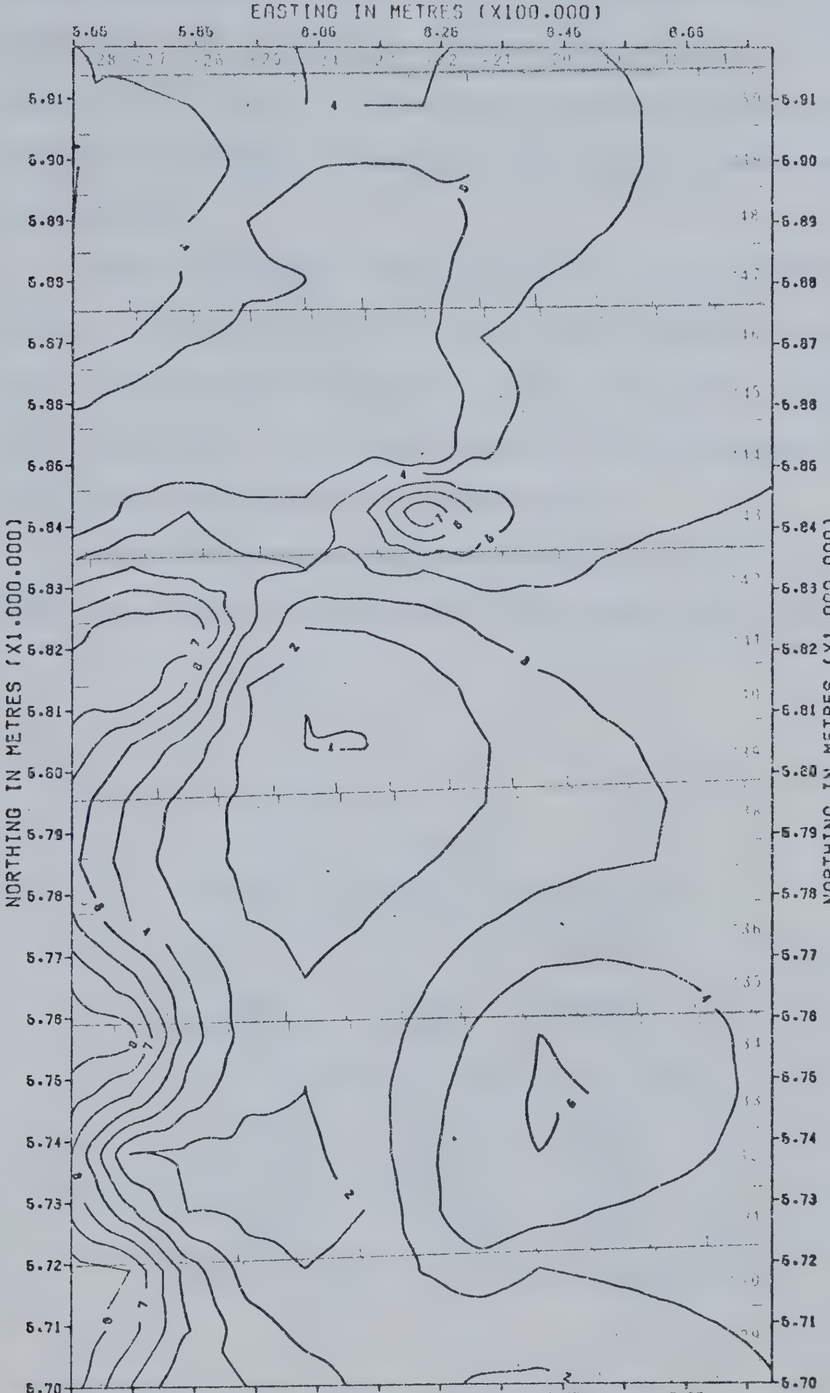
The estimate of the coal resources in the study area is based on the following formula (Averitt, 1969):

$$\text{Tons per township} = \frac{36 \times \text{VOL} \times \text{DW} \times \text{SG}}{2{,}000}$$

where 36 is number of sections per township; VOL is the volume of coal in cubic feet in one section (one square mile), i.e., 5,280 x 5,280 x thickness in feet; DW is density of water (62.4 lb/cu ft); and SG is specific gravity of coal (1.30 gm, an average selected for the subbituminous coal in Saskatchewan).

Substituting in the formula, one obtains a value of 40.7 million short tons per township for a one-foot coal seam.

An estimated value of 19,400 million short tons of coal (including all seams 2 feet thick or thicker) was obtained for the Mannville Group in the study area. The major concentration of coal is near the Alberta-Saskatchewan border from Townships 31 to 35 and 39 to 43 (figure 7.1). If only seams of 3 feet thick or thicker are considered, the estimated value drops to 16,800 million tons, i.e., 86.6% of the initial value. If only seams of 5 feet or greater thickness are considered, the estimated value is further reduced to 8,500 million tons or 43.8% of the total.



ISOPACH MAP OF SEAM 8.

AREA: TWP.29-60. RGE.18-28 W3.
CONTOUR INTERVAL = 1 FT.

SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

Fig. 7.6

Table 7.1 summarizes these values. The resource estimates on the two major coal seams (seams 3 and 8) are shown in Tables 7.2 and 7.3. If seams of 2 feet thick or thicker are considered, seam 3 constitutes 16.1% of the total resource estimated for the study area while seam 8 constitutes 49.3%.

Latour and Chrismas (1970) estimated a total of 12,014 million tons of coal resources in place in southern Saskatchewan. This coal is of Tertiary and/or Late Cretaceous age and includes all seams greater than three feet thick. Within the study area, the corresponding resources in the Mannville Group are 13,879 million tons.

Yurko (1976) made a similar estimate of the coal resources of the Cretaceous System in Alberta based on one petroleum borehole per township.

Table 7.1

Resource Estimate of Mannville Coal
(in millions of short tons)

Seam Thickness	Total Coal	Percent of Total
≥2 feet	19,414	100.0%
≥3 feet	16,809	86.6%
≥4 feet	13,879	71.5%
≥5 feet	8,506	43.8%
>5 feet	6,064	31.2%

Table 7.2

Resource Estimate of Seam 3
(in millions of short tons)

Seam Thickness	Total Coal	Percent of Total
≥2 feet	3,134	100.0%
≥3 feet	2,727	87.0%
≥4 feet	1,872	59.7%
≥5 feet	1,058	32.8%
>5 feet	244	7.8%

Table 7.3

Resource Estimate of Seam 8
(in millions of short tons)

Seam Thickness	Total Coal	Percent of Total
≥2 feet	9,605	100.0%
≥3 feet	8,221	85.6%
≥4 feet	7,123	74.2%
≥5 feet	4,518	47.0%
>5 feet	3,297	34.3%

Table 7.4

Coal Resources in Various Areas
(in millions of short tons)

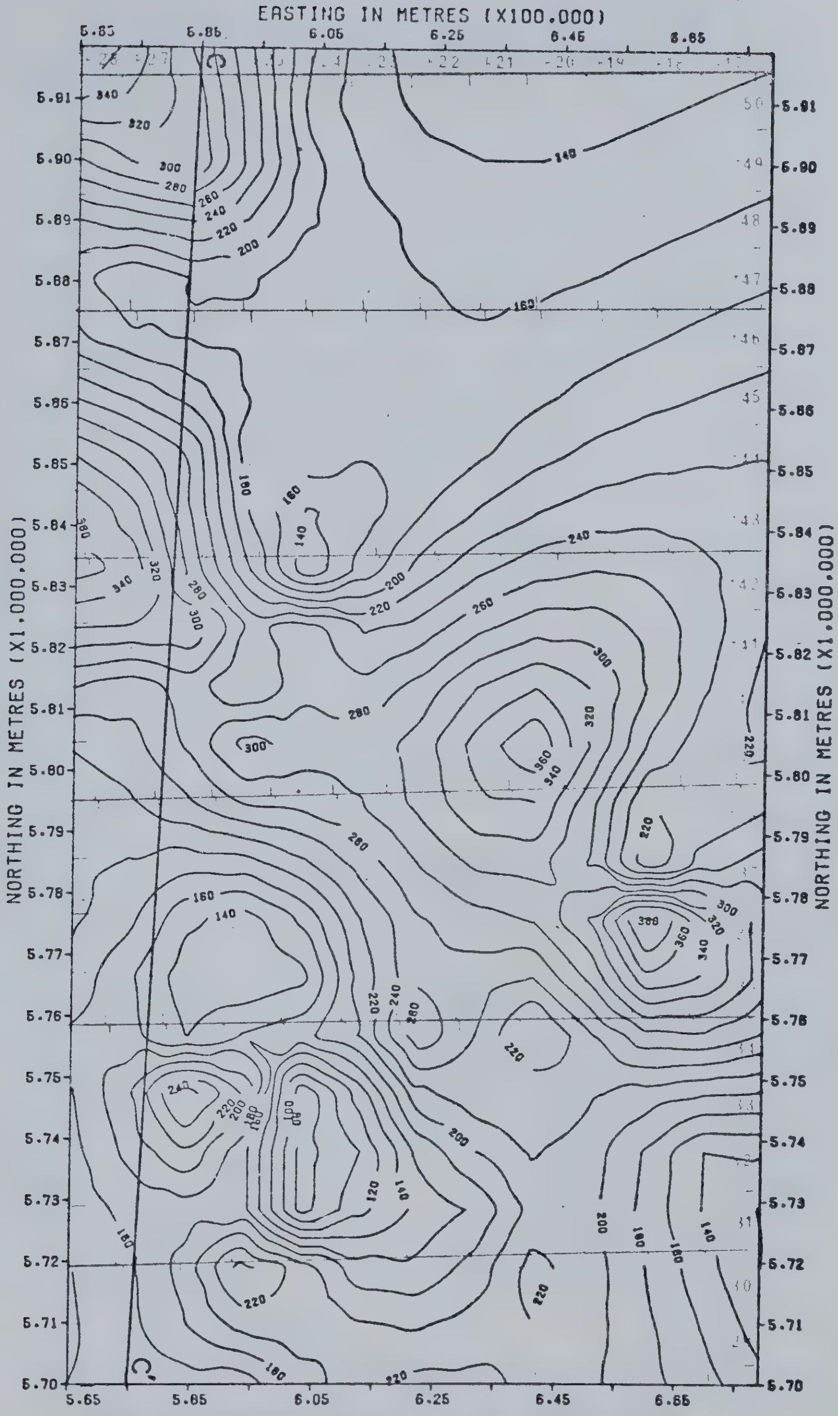
Seam Thickness	Mannville Group (Lower Cretaceous)		Tertiary and/or Late Cretaceous Southern Sask. Latour and Chrismas (1970)
	Alberta Yurko (1976)	W.C. Sask. This Study	
≥2 feet	627,978	19,414	-
≥4 feet	-	13,879	12,014
>5 feet	401,724	6,064	-

He obtained a total estimate for the entire Mannville Group over the whole province of 627,978 million tons for seams 2 feet thick or thicker; his estimate for seams thicker than 5 feet was 401,724 million tons which is 64% of the total (table 7.4).

C. VERTICAL VARIABILITY OF THE COAL SEAMS

In the Mannville Group, up to 10 seams are distributed through up to 280 feet of strata. A study of the vertical distribution of coal seams in such a stratigraphic section can provide valuable insights into palaeoenvironmental conditions in Mannville time. The technique employed involved calculation of the centre of gravity of coal seams in each borehole using the procedure of Krumbein and Libby (1957), and presenting the data in map form (figure 7.7).

The centre of gravity map shows the weighted mean position of the coal in terms of its distance from the top of the Mannville Group. It should be noted that the data have been extrapolated into areas where no coal or no control points occur. Within the study area, the centre of gravity ranges from 140 to 380 feet below the top of the Mannville. To express the centre of gravity in terms of the percentage of the thickness of Mannville as measured from the top of the group, the relative centre of gravity is plotted (figure 7.8). In the northern part of the area, the relative centre of gravity falls mainly in the 40% to 60% range, indicating that most of the coal is approximately at the midpoint of the Mannville Group. In the southern area, the relative centre of gravity drops to the 60% to 80% range, showing that the seams are aggregated near the base of the Mannville (figure 7.9).

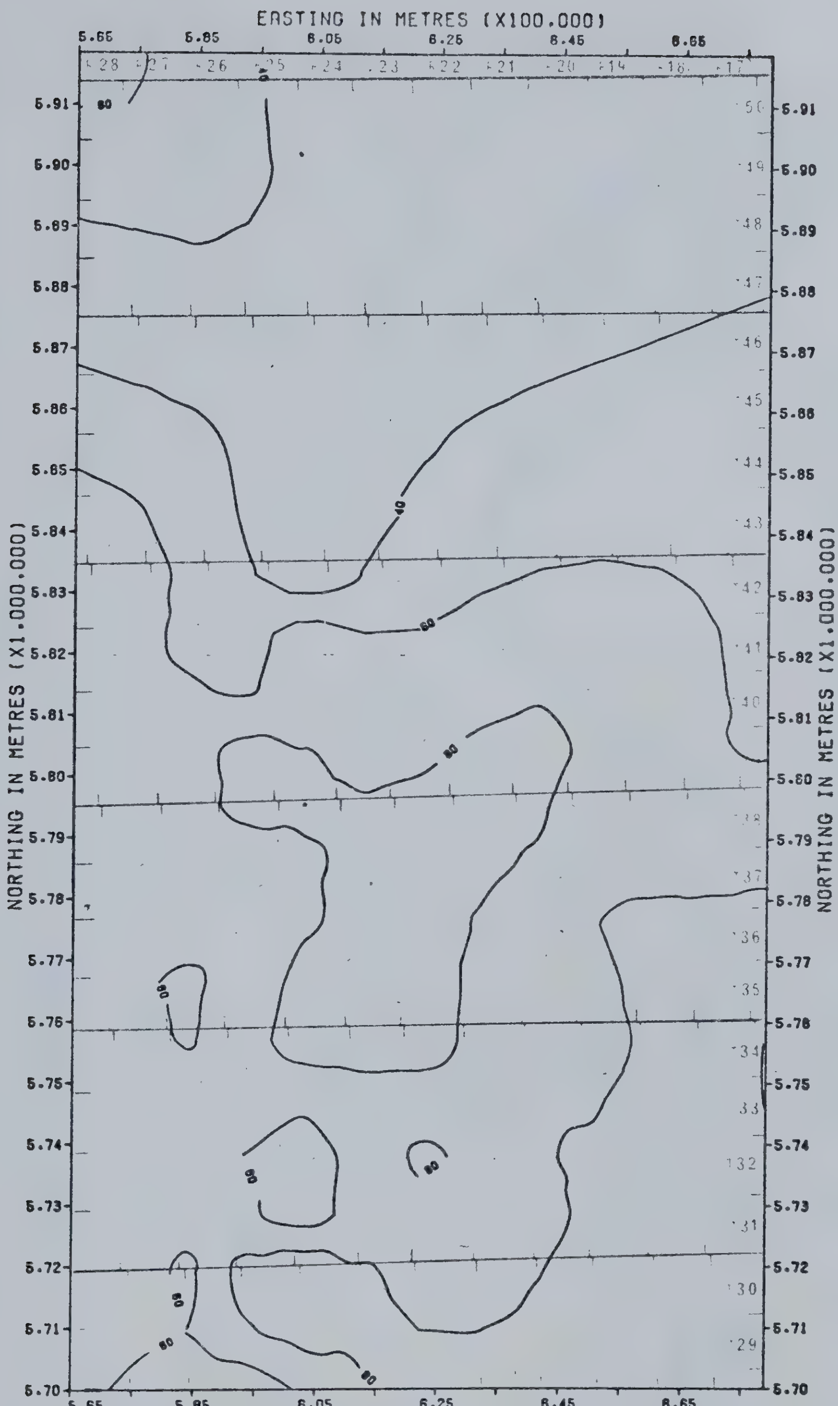


CENTRE OF GRAVITY MAP OF COAL SEAMS.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 20 FT.
DATUM : TOP OF MANNVILLE.

Fig.7.7

SCALE 0 1 2 3 (X10KM)
0 10 20 (MILES)



RELATIVE CENTRE OF GRAVITY OF COAL SEAMS.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 20 %.

SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

Fig. 7.8

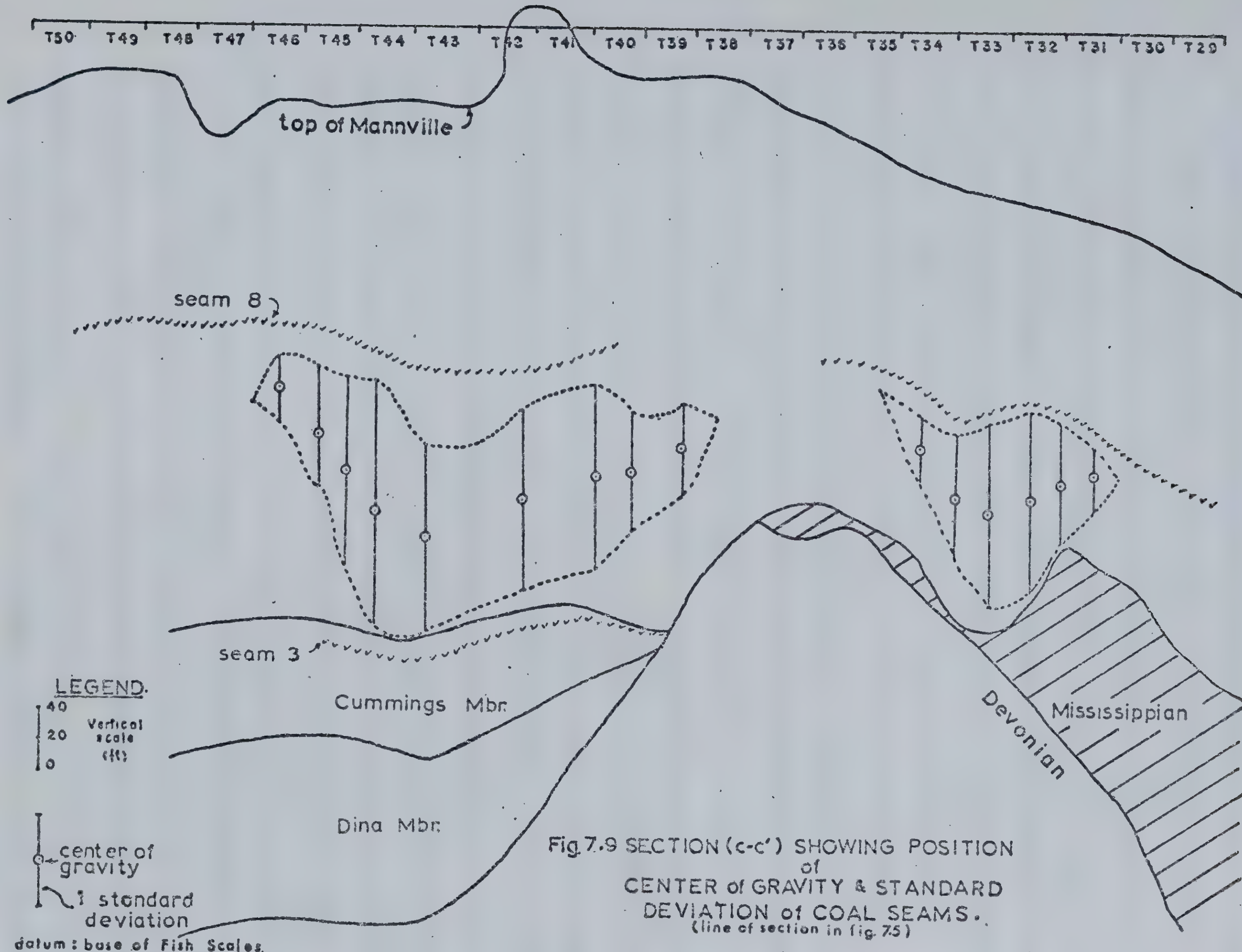
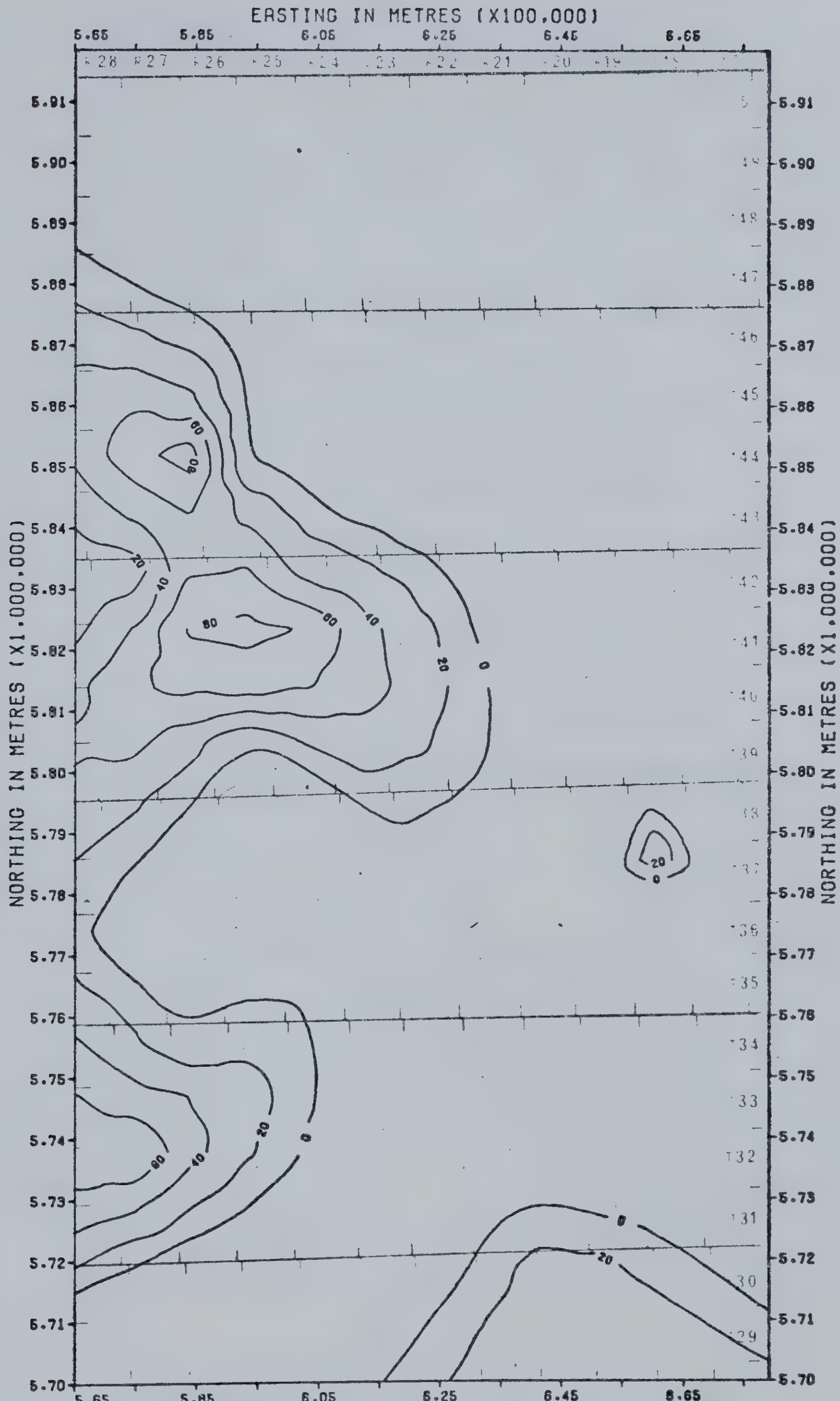


Fig. 7.9 SECTION (c-c') SHOWING POSITION of CENTER of GRAVITY & STANDARD DEVIATION of COAL SEAMS.
(line of section in fig. 7.5)

Information on how the seams are actually distributed in the Mannville Group is provided by the standard deviation maps (figures 7.10 and 7.11). The standard deviation, in this case, is that thickness of the formation, measured from the centre of gravity, which includes 68% of the coal. The relative standard deviation map (figure 7.11) shows the percentage of the Mannville strata being included in one standard deviation. Zero standard deviation occurs where there are no control points, or only one seam is present in the well. As the value increases, the spreading out of the seams also increases. The major portion of the coal-bearing area lies below the 60-foot contour, indicating that within this area, 68% of the coal occurs within 60 feet of the centre of gravity (figure 7.10). However, in the southwestern part of the area, plus or minus 60 feet (i.e., 120 feet in total) is almost half the thickness of the entire Mannville Group. This can be illustrated by reference to the relative standard deviation map (figure 7.11) which shows the percentage of the Mannville Group included in one standard deviation. Like standard deviation, zero relative standard deviation indicates no coal or only one seam in a well. As the value increases, the percentage of the formation included in a standard deviation also increases. For example, within the 20% contour, in order to account for 68% of the coal in a well, 20% of the formation on either side of the centre of gravity must be included that is, a total of 40% of the formation. Two standard deviations will account for 95% of the coal, therefore inasmuch as the major part of the study area lies below the 20% relative standard deviation contour, on the average, 95% of the coal in a well occurs within an 80% thickness interval of the Mannville sediments. It is apparent therefore, that the coal seams in the Mannville Group are scattered throughout the group and are not aggregated in any one part of it.



STANDARD DEVIATION MAP OF COAL SEAMS.

AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 20 FT.
DATUM:CENTER OF GRAVITY OF COAL SEAMS.

SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

Fig.7.10

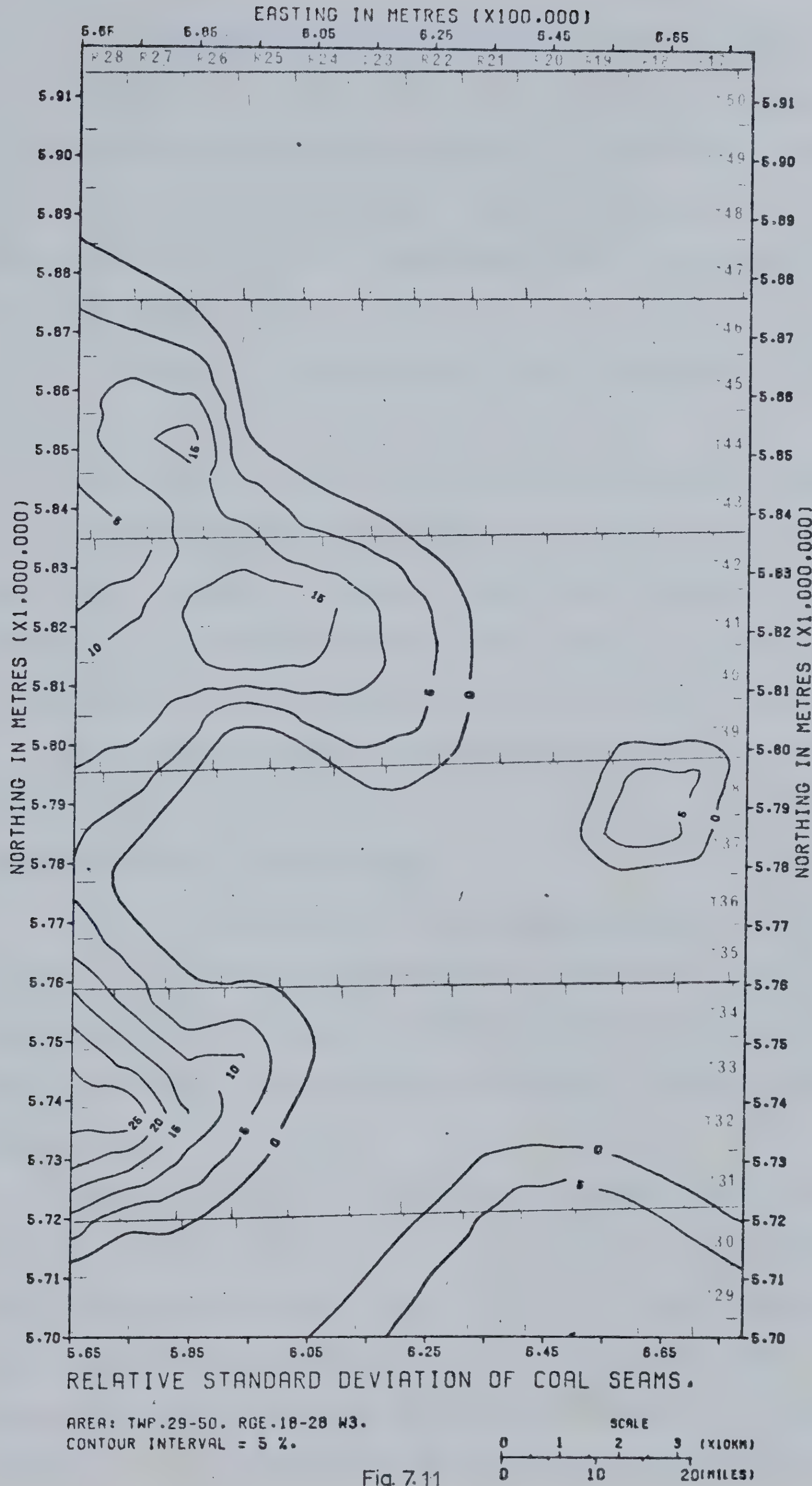

EASTING IN METRES (X100.000)
NORTHING IN METRES (X1,000,000)
R28 R27 R26 R25 R24 R23 R22 R21 R20 R19
RELATIVE STANDARD DEVIATION OF COAL SEAMS.
AREA: TWP.29-50. RGE.18-28 W3.
CONTOUR INTERVAL = 5 %.
SCALE
0 1 2 3 (X10KM)
0 10 20(MILES)

Fig. 7.11

D. INTERPRETATION OF THE VERTICAL VARIABILITY MAPS

A comparison among the total coal thickness distribution (figure 7.1), the centre of gravity map (figure 7.7), the standard deviation map (figure 7.10) and the isopach map of the Mannville Group (figure 6.4) shows that where major coal accumulation occurs, the following conditions generally exist:

(1) The Mannville sediments are thick, indicating a palaeotopographic low (figure 6.4);

(2) The number of seams and/or the net thickness of coal (figure 7.1) has a direct relationship to the centre of gravity of coal (figure 7.7). When either the number of seams or the net coal thickness is large, the value for the centre of gravity is also large, i.e., the centre of gravity is further down from the top of the Mannville; by the same token, when

(3) The number of seams and/or the net thickness of coal (figure 7.1) is large, the standard deviation of coal is large, i.e., the vertical scattering of the seams increases.

It has to be emphasized that these conditions are generalized relationships. Statistical treatment of the geophysical log data using linear regression shows that there is little correlation among the parameters discussed. However, by superimposing the maps, the qualitative relationships mentioned can be shown.

These conditions can be explained by hypothesizing the depositional environments during Mannville time in the study area as follows. The palaeotopographic low areas became the sites of either swampy areas or stream channels. In these swampy areas, coal was deposited. Log jams along river banks (see Price, 1971) may also have been a source of coal accumulation. As sedimentation of the Mannville Group continued, the

loci of these low-lying areas migrated laterally, leading to the present areal distribution pattern of the coal.

Condition 2 arises since the majority of the seams (seam 1 to 8) were deposited in the lower portion of the Mannville Group. This indicates that the supply of sediments was in pace with subsidence, leading to equilibrium (or stable) conditions for the continual deposition of coal. However, the decrease in coal deposition after seam 8 signifies either an increase in sediments supply or a rapid subsidence of the basin. The former case gives rise to a dry continental environment, whereas rapid subsidence will lead to marine transgression. Since the portion of the Mannville Group above seam 8 is of continental origin, the writer adopts the theory that sediment supply increased after the deposition of seam 8.

If the loci of deposition of coal was static for a long period of time during the deposition of the Mannville Group, there would be fewer seams and each seam would probably be much thicker. However, this was not the case within the study area as indicated by the standard deviation map (figure 7.10) and the net coal thickness map (figure 7.1). The frequent change of depositional loci led to increasing scatter, both geographically and stratigraphically, of coal distribution in the Mannville Group.

A study of the position of the centre of gravity and the standard deviation of coal (see also figure 7.9) in the study area further shows that north of the Battleford Arch, the Mannville sediments can be divided into three zones; a coal-bearing zone being sandwiched between lower and upper non-coal-bearing zones. The lower non-coal-bearing zone consists of the Dina and the Cummings Members, the overlying coal-bearing zone extends approximately from the top of the Cummings Member to the top of

the Borradaile Member (i.e., seam 8), and the upper non-coal-bearing zone includes those Mannville beds overlying seam 8.

South of the Battleford Arch, the lower non-coal-bearing zone is absent and the median coal-bearing zone is bounded by the sub-Cretaceous unconformity below and seam 8 above. The overlying non-coal-bearing zone has the same vertical extent as its northern counterpart (figure 7.9). The correlation between the coal-bearing zones both north and south of the Battleford Arch further supports the hypothesis that during the deposition of the Dina and the Cummings Members in the northern part of the study area, deposition of the Undifferentiated Mannville Group in the south had not begun (see discussion in section D, Chapter 4).

Chapter 8

AREAL VARIATION OF THICKNESS OF SEAM 8

A. THEORY AND APPLICATION

Matheron (1963) defined a regionalized variable as one that has a definite value at each point in space. Examples for this kind of variable are coal seam thickness, ore grade, water chemistry in an aquifer, etc.. The value of these variables may change from one point to another and the spatial relationship of this change (i.e., how rapid is the change from point to point) is important to the geologist. The tool to examine this spatial relationship is the variogram which is a statistical measure of the degree of areal variation or lateral continuity of a variable. A full mathematical treatment of the variogram is outside the scope of this thesis. The reader is referred to the publications by Matheron (1963), David (1974) and Huijbregts (1975). The following is an account of the basic concept of the variogram.

Suppose one wants to compare, say, coal seam thickness at two points (x) and (x+h) at a distance h units apart, one would examine the thickness difference at the two points without being concerned with the sign (positive or negative) of the difference. The simplest way to eliminate the sign is to square the difference. To express this in mathematical form:

$$2\gamma(\vec{h}) = [th(x) - th(x+h)]^2$$

where $2\gamma(\vec{h})$ = the variogram; th(x) = thickness at point x; and th(x+h) = thickness at point (x+h), h units away from point x. Usually, the semi-variogram, $\gamma(\vec{h})$, is used.

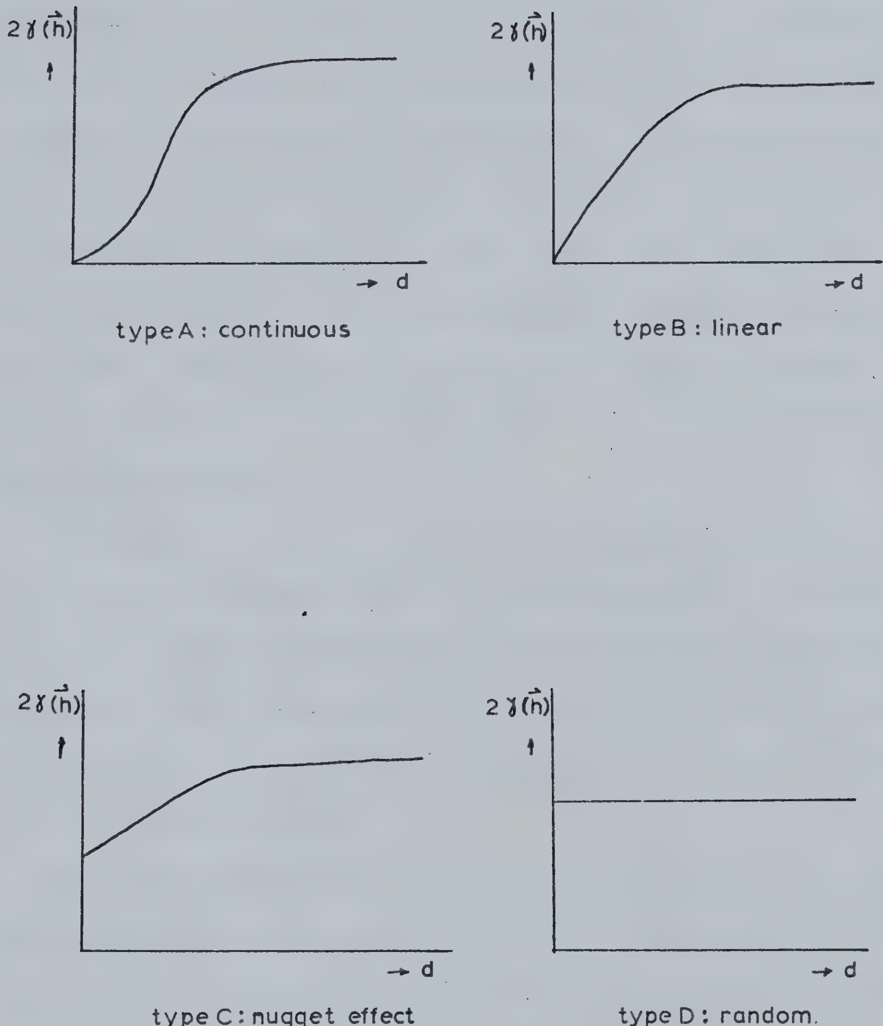
The variogram, $2\gamma(\vec{h})$, is a vector and takes the direction of h, the separation of the points, into account. Variogram values refer to pairs of points; for example, if one has four data points A, B, C, and D, one will have a total of 6 variogram values, for the pairs AB, AC, AD, BC, BD, CD, that is, $[(n-1)+(n-2)+\ldots+(n-n)]$ values. To simplify matters, variogram values are grouped into classes according to the distance between the pairs and the average value of the class is taken as the representative value for the class. Hence, for a particular class, say within 0 to 500 feet, the variogram value can be written as:

$$2\gamma(\vec{h}) = \frac{1}{N} \sum_{i=1}^{N} [th(x) - th(x+h)]^2$$

where $(\vec{h})$ denotes the direction of the variogram value, N is the total number of data point pairs in that class, i.e.,

$$2\gamma(\vec{h}) = \text{average } [th(x) - th(x+h)]^2$$

When semi-variogram values are plotted versus distance between points four general types of curves (Matheron, 1963) may be recognized (figure 8.1). The continuity of the variable under consideration is reflected by the rate of increase of $\gamma(\vec{h})$ for small increments in distance. Type A has a parabolic trend at the origin and the variable under consideration (e.g., bed thickness) has a high continuity. Type B shows that the change of $\gamma(\vec{h})$ is uniform, typifying, for example, a relatively uniform sedimentary deposit where changes usually occur very slowly. In other cases, again using a sedimentary example, deposition may be in the form of lenses or even



<u>LEGEND</u>: $2\gamma(\vec{h})$: variogram.
d : distance.

Fig. 8.1 TYPES of VARIOGRAM.*
(*after Matheron 1963)

nodules, often concentrated in small areas, with rapid changes occurring over very short distances. Curve C shows the effect of this rapid change; the positive intercept (Co) is known as the nugget effect. The nugget effect may occur for a number of reasons, such as poor sampling resolution (for example of geophysical borehole logs) or erratic distribution of the variables. It increases the variance of the variable under consideration by the amount equal to Co and also implies that if one goes back to sample the same site, the results will differ (see David, 1974, p. 62). When the semi-variogram values, $\gamma(\vec{h})$, are independent of each other regardless of the distance between two samples, a curve of type D is produced. This is common in gold deposits for example and, it is called the random (or pure nugget effect) type.

The zone (or range) of influence of a data point is the distance beyond which the influence of the data point disappears. In the variogram, this zone is represented by the distance at which the curve reaches a plateau (the sill). Along the sill, the rate of change of the variogram is independent of the distance. In curve D, the zone of influence is zero for all practical purposes.

As has been mentioned, the variogram, $2\gamma(\vec{h})$, is a vector, and therefore when specifying the zone (or range) of influence, the direction in which the zone is effective must be taken into consideration. For this reason, the word "zone" (or range) is preferable to "radius" which implies the influence is the same in all directions. Because of this directional component, if one compares variograms taken in different directions and plots the corresponding results, the zone of influence for the different curves may not be the same. If the zone of influence is the same in all

directions, the condition is called isotropic, otherwise the term anisotropic is applied to the condition where the zone of influence varies with direction. In figure 8.2, for example, the zone (or range) of influence in the north-south direction is approximately twice as much as that in the east-west direction. By using the zone of influence and its direction, one can reconstruct the major axis of continuity of the deposit with some degree of certainty. Venter (1975) has discussed the use of the variogram to increase the reliability and validity of the conventional polygon method of calculating coal reserves. This is achieved first by limiting the maximum area-of-influence by any one drill hole, and then by assigning the width of the boundary zone of a deposit according to the zone of influence obtained from the variogram.

In the present study, it is intended to use the variogram to gain some insight on the palaeodrainage direction during Mannville time in the study area. It is hypothesized that if coal was deposited on the stream floodplains, deposits would have a greater extent and consistency parallel to the stream flow than in the transverse direction. If such is the case, then the continuity of the coal seam thickness will be greater in the direction parallel to the stream flow. This continuity should be reflected by the zone of influence in the variogram; the greater the continuity, the longer the zone of influence. Hence, by obtaining the zone of influence in various directions, it may be possible to reconstruct the palaeodrainage direction.

One hundred and one wells (figure 8.3) were used to depict the thickness of seam 8 in part of the study area. The resulting variograms are presented in figures 8.4 to 8.10. Seam 8 was chosen for the vario-

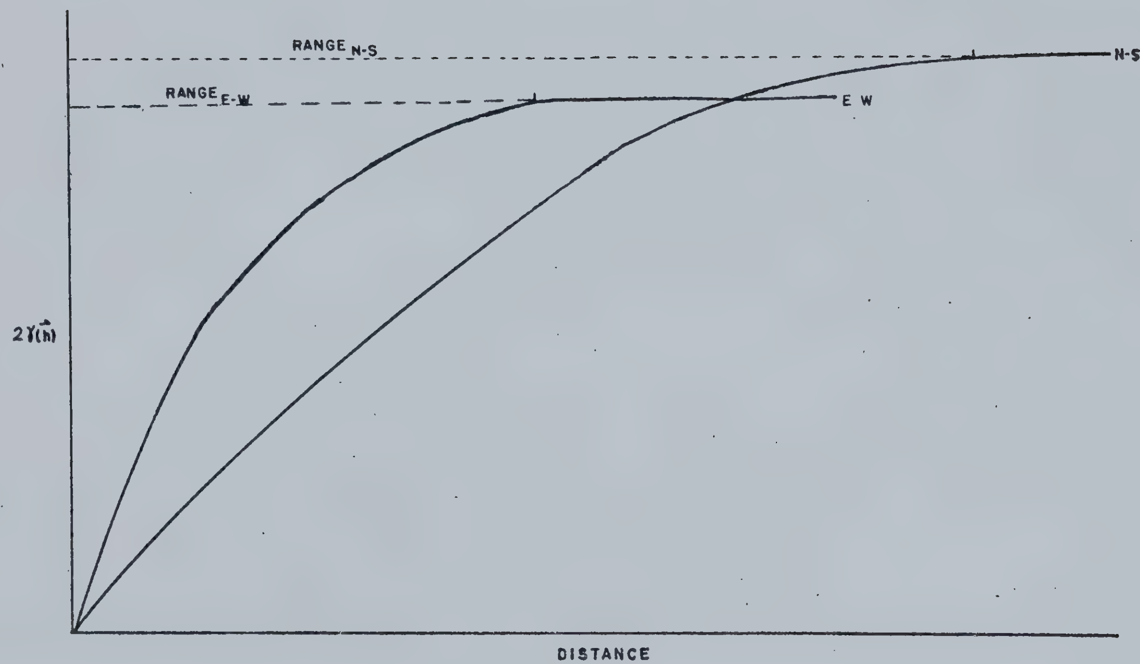
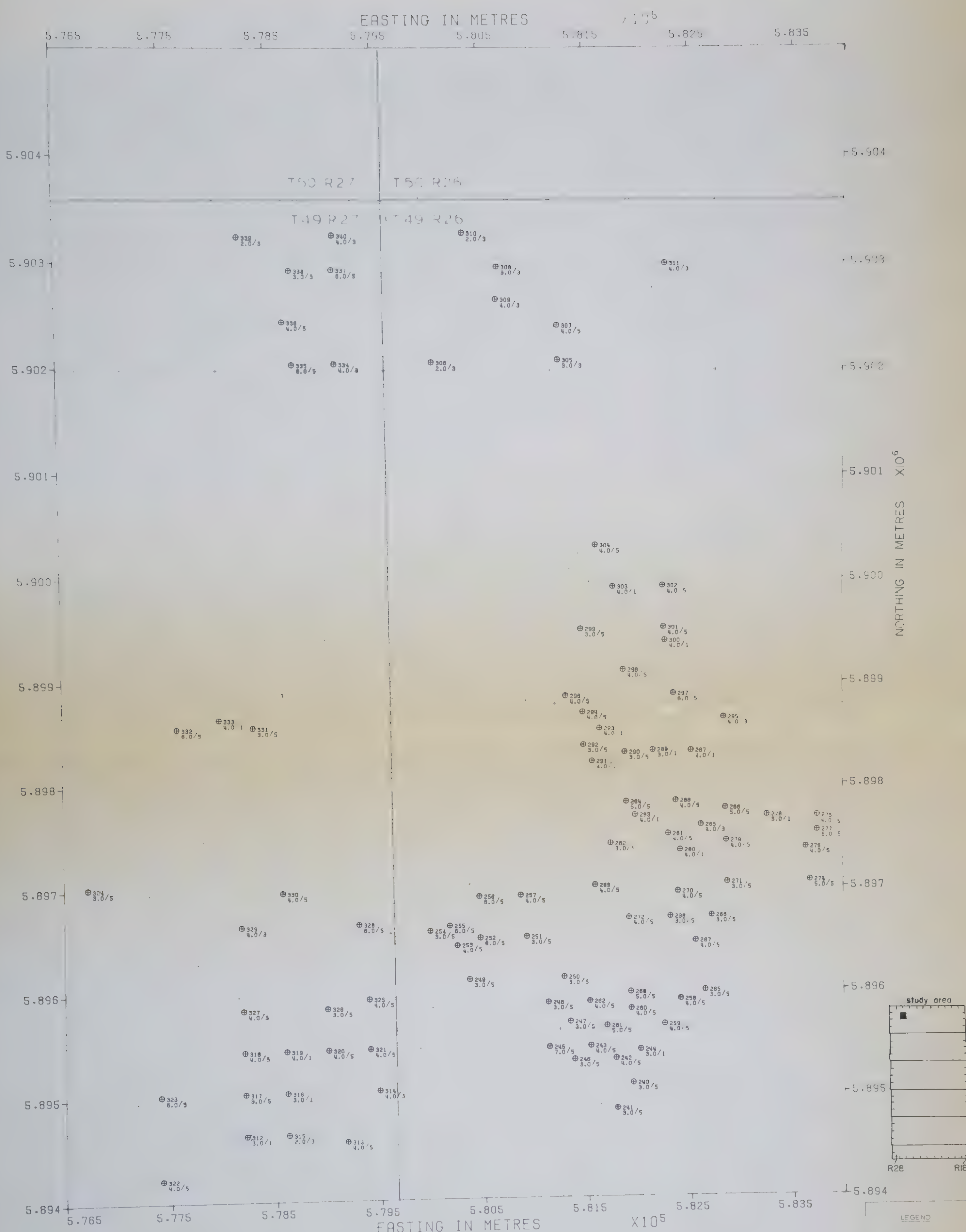


Fig 8.2 ANISOTROPIC VARIOGRAM SHOWING DIFFERENCE IN RANGE IN DIFFERENT DIRECTIONS.



CONTROL WELLS LOCATION FOR VARIOGRAM STUDY.

AREA: TWP.49, RGE.26-27 W3.

Fig. 8.3

VARIOGRAM WITH A FIELD OF 180. DEGREES IN EACH DIRECTION

STEP IN METERS = 500.0000

UPPER LIMIT FOR Z = 30.0000

GENERAL MEAN OF Z = 3.9208

GENERAL VARIANCE OF Z = 0.9937

DISTANCE IN METERS	NB. OF PAIRS	DRIFT	VARIOGRAM	AVERAGE DISTANCE
0 ---- 500	147	0.007	0.8061	369.7
500 ---- 1000	348	0.172	0.8994	771.0
1000 ---- 1500	419	0.048	0.8759	1260.5
1500 ---- 2000	453	0.009	0.8477	1750.6
2000 ---- 2500	483	0.064	1.1004	2249.1
2500 ---- 3000	435	0.078	0.9793	2743.5
3000 ---- 3500	390	0.051	0.9538	3240.8
3500 ---- 4000	383	0.031	0.8355	3736.1
4000 ---- 4500	339	0.015	0.8274	4252.1
4500 ---- 5000	307	0.049	0.8159	4746.8
5000 ---- 5500	266	-0.045	1.0884	5247.4
5500 ---- 6000	233	0.047	1.1998	5729.1
6000 ---- 6500	218	-0.128	1.2523	6231.4
6500 ---- 7000	193	-0.420	1.4171	6732.4
7000 ---- 7500	166	0.032	1.0806	7234.4
7500 ---- 8000	123	-0.317	1.3618	7737.2
8000 ---- 8500	80	-0.475	1.5500	8213.2
8500 ---- 9000	32	-0.375	1.1562	8695.6
9000 ---- 9500	9	-0.333	0.8333	9174.2
9500 ----10000	1	-2.000	2.0000	9526.6
10000 ----10500	1	0.0	0.0	10035.7

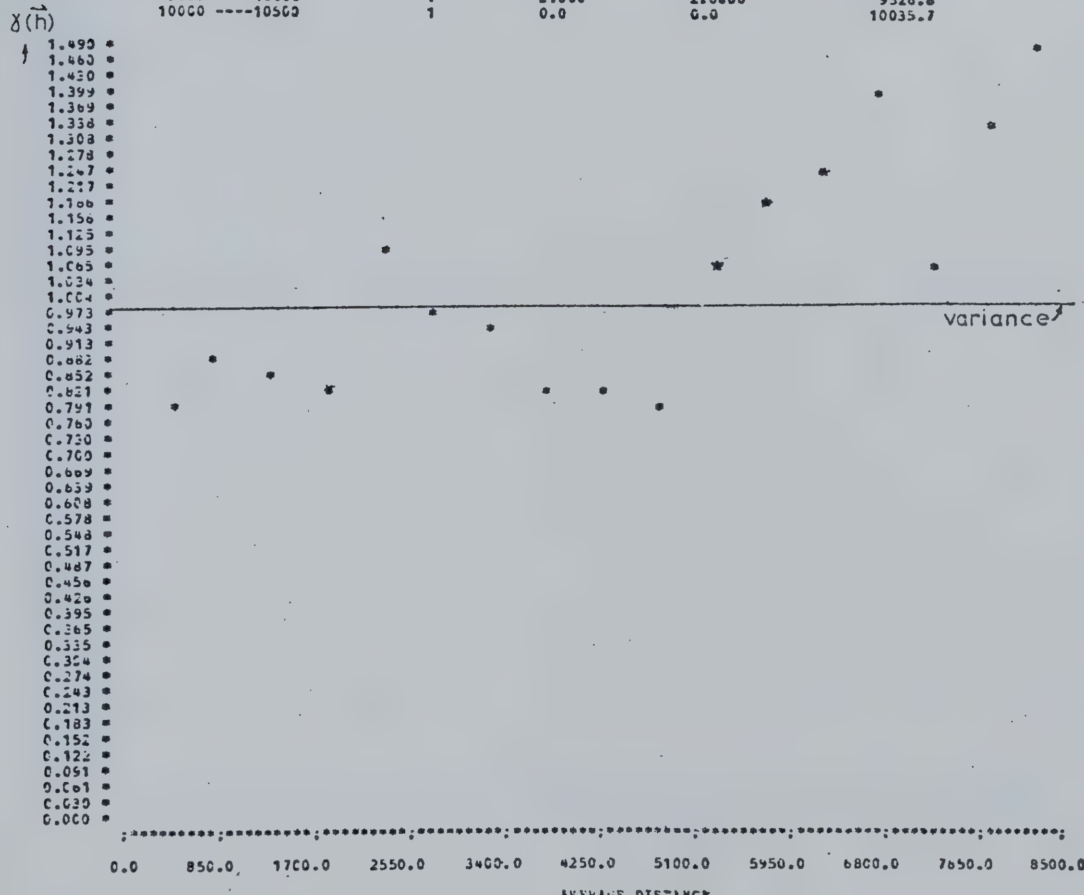


Fig 8.4 GENERAL VARIAGRAM of SEAM THICKNESS.

VARIOGRAM WITH A FIELD OF 90. DEGREES IN EACH DIRECTION

STEP IN METERS : 500.0000

UPPER LIMIT FOR Z : 30.0000

GENERAL MEAN OF Z : 3.9208

GENERAL VARIANCE OF Z : 0.9937

DISTANCE IN METERS	NB. OF PAIRS	DRIFT	VARIOGRAM	AVERAGE DISTANCE
0 ---- 500	72	0.097	0.7431	372.1
500 ---- 1000	172	0.186	0.7616	775.3
1000 ---- 1500	217	-0.005	0.6705	1266.2
1500 ---- 2000	253	0.170	0.6739	1745.6
2000 ---- 2500	264	0.087	0.9375	2253.7
2500 ---- 3000	228	0.083	0.8487	2751.2
3000 ---- 3500	177	0.102	0.9096	3244.2
3500 ---- 4000	168	-0.131	0.8274	3730.3
4000 ---- 4500	139	-0.094	0.9532	4237.1
4500 ---- 5000	145	0.021	0.8241	4755.2
5000 ---- 5500	138	-0.355	1.1268	5274.0
5500 ---- 6000	146	-0.110	1.0685	5742.0
6000 ---- 6500	182	-0.220	1.2747	6238.6
6500 ---- 7000	172	-0.453	1.4593	6732.6
7000 ---- 7500	179	0.011	1.0726	7238.1
7500 ---- 8000	123	-0.317	1.3618	7737.2
8000 ---- 8500	80	-0.475	1.5500	8213.2
8500 ---- 9000	32	-0.375	1.1562	8698.6
9000 ---- 9500	9	-0.333	0.8333	9174.2
9500 ----10000	1	-2.000	2.0000	9526.6
10000 ----10500	1	0.0	0.0	10035.7

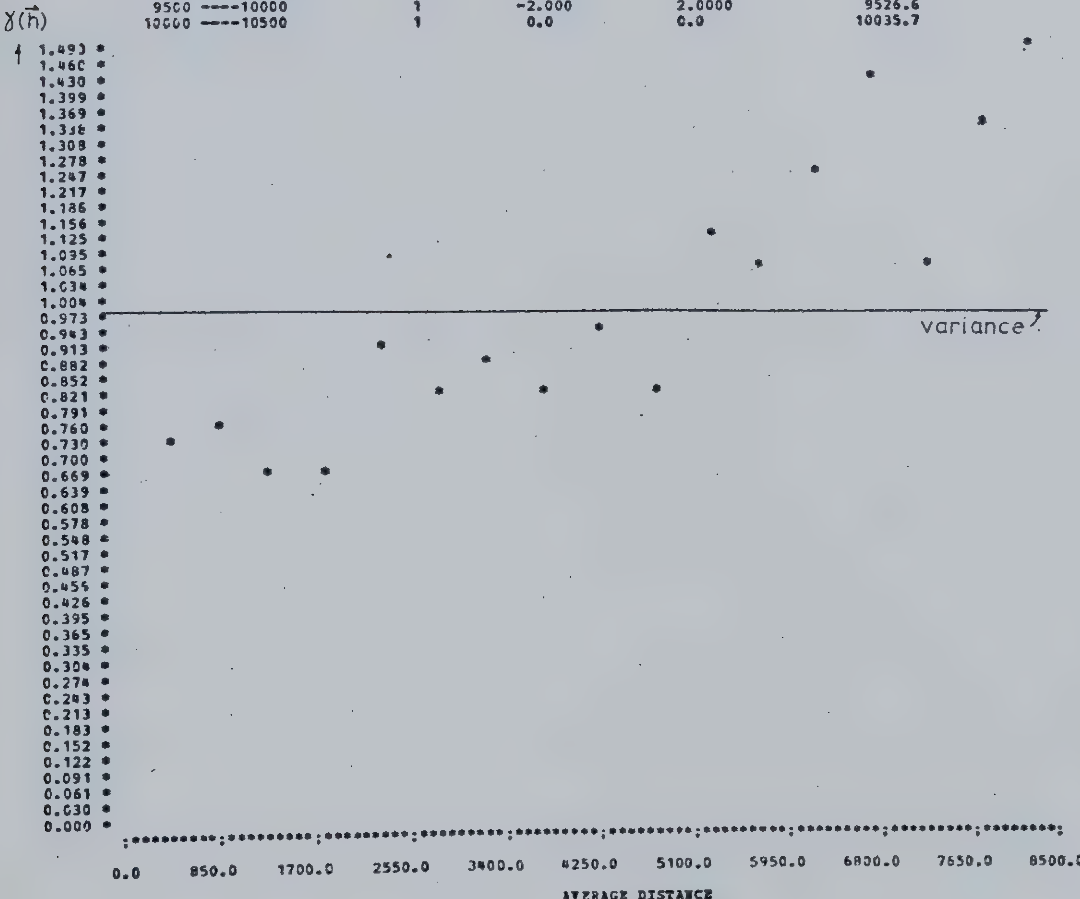


Fig 8.5 VARIOGRAM with direction = 0°-180°

VARIOGRAM WITH A FIELD OF 90. DEGREES IN EACH DIRECTION

STEP IN METERS # 500.0000

UPPER LIMIT FOR Z # 30.0000

GENERAL MEAN OF Z # 3.9208

GENERAL VARIANCE OF Z # 0.9937

DISTANCE IN METERS	NB. OF PAIRS	DRIFT	VARIOGRAM	AVERAGE DISTANCE
0 ---- 500	73	0.055	0.7397	369.9
500 ---- 1000	172	0.279	0.8139	779.2
1000 ---- 1500	224	0.080	0.7723	1268.7
1500 ---- 2000	248	0.028	0.8246	1748.6
2000 ---- 2500	297	0.030	1.0286	2247.8
2500 ---- 3000	285	0.172	0.9947	2745.5
3000 ---- 3500	232	0.112	1.0345	3235.3
3500 ---- 4000	238	0.076	0.7521	3731.1
4000 ---- 4500	210	0.010	0.6619	4244.2
4500 ---- 5000	192	0.193	0.6745	4742.7
5000 ---- 5500	155	-0.071	1.0161	5251.7
5500 ---- 6000	126	0.071	1.1865	5732.8
6000 ---- 6500	134	-0.254	1.1418	6227.4
6500 ---- 7000	108	-0.593	1.3333	6727.2
7000 ---- 7500	109	-0.018	0.8716	7232.4
7500 ---- 8000	73	-0.411	1.2877	7734.2
8000 ---- 8500	49	-0.347	1.3367	8220.1
8500 ---- 9000	23	-0.435	1.1304	8711.6
9000 ---- 9500	8	-0.250	0.8750	9182.2
9500 ----10000	1	-2.000	2.0000	9526.6
10000 ----10500	1	0.0	0.0	10035.7

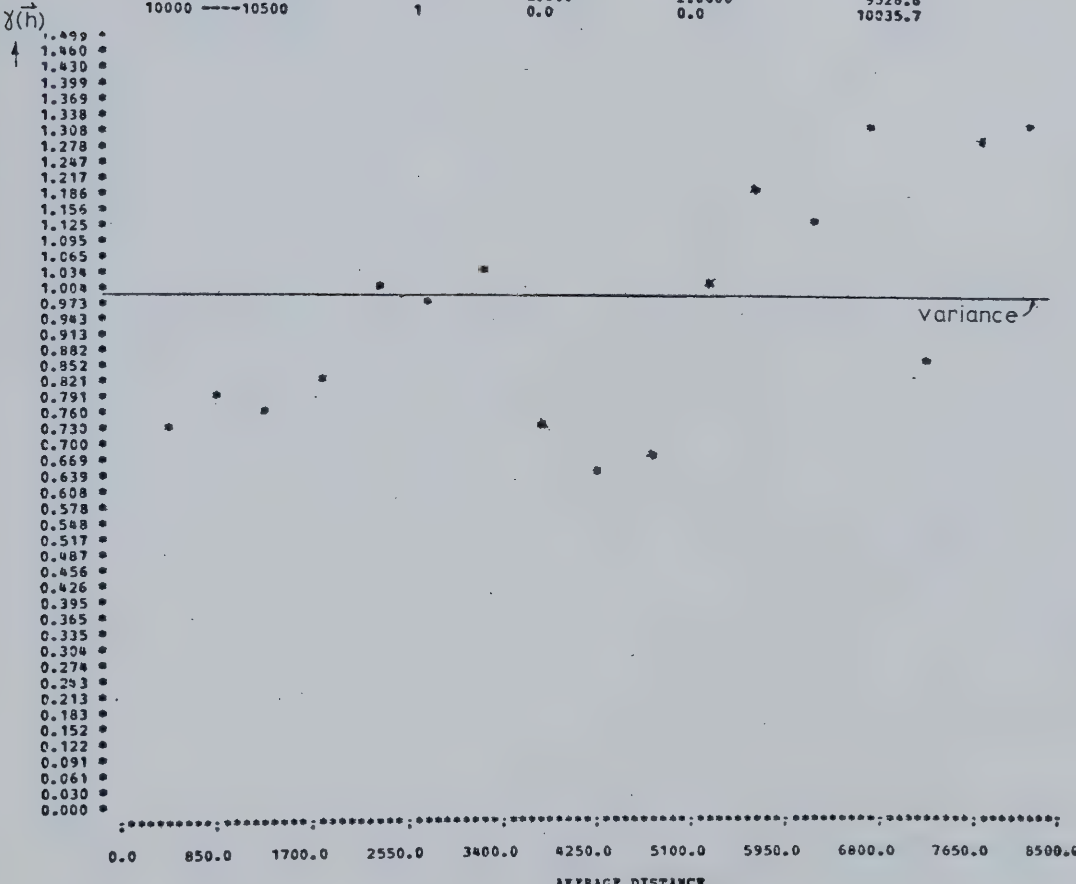


Fig 8.6 VARIOGRAM with direction = 30° or 210°

VARIOGRAM WITH A FIELD OF 90. DEGREES IN EACH DIRECTION

STEP IN METERS = 500.0000

UPPER LIMIT FOR Y = 30.0000

GENERAL MEAN OF Z = 3.9208

GENERAL VARIANCE OF Z = 0.9937

DISTANCE IN METERS	NB. OF PAIRS	DRIFT	VARIOGRAM	AVERAGE DISTANCE
0 ---- 500	74	-0.081	0.9595	372.7
500 ---- 1000	178	0.146	0.8708	782.9
1000 ---- 1500	209	0.038	0.8564	1268.4
1500 ---- 2000	214	-0.061	1.1238	1753.2
2000 ---- 2500	279	-0.129	1.2007	2236.7
2500 ---- 3000	259	0.228	1.1757	2731.1
3000 ---- 3500	233	-0.004	1.0493	3238.9
3500 ---- 4000	243	0.012	0.8580	3736.6
4000 ---- 4500	204	-0.162	0.6887	4251.3
4500 ---- 5000	186	0.161	0.6774	4750.8
5000 ---- 5500	135	0.104	0.9556	5242.2
5500 ---- 6000	106	0.396	1.1792	5730.9
6000 ---- 6500	68	0.162	0.9779	6193.4
6500 ---- 7000	42	-0.500	0.9405	6749.5
7000 ---- 7500	22	0.182	0.4545	7207.8
7500 ---- 8000	18	-0.278	0.8056	7719.1
8000 ---- 8500	17	-0.294	0.9706	8230.2
8500 ---- 9000	8	-0.750	1.7500	8758.8
9000 ---- 9500	6	0.0	0.8333	9199.3
9500 ----10000	1	-2.000	2.0000	9526.6
10000 ----10500	1	0.0	0.0	10035.7

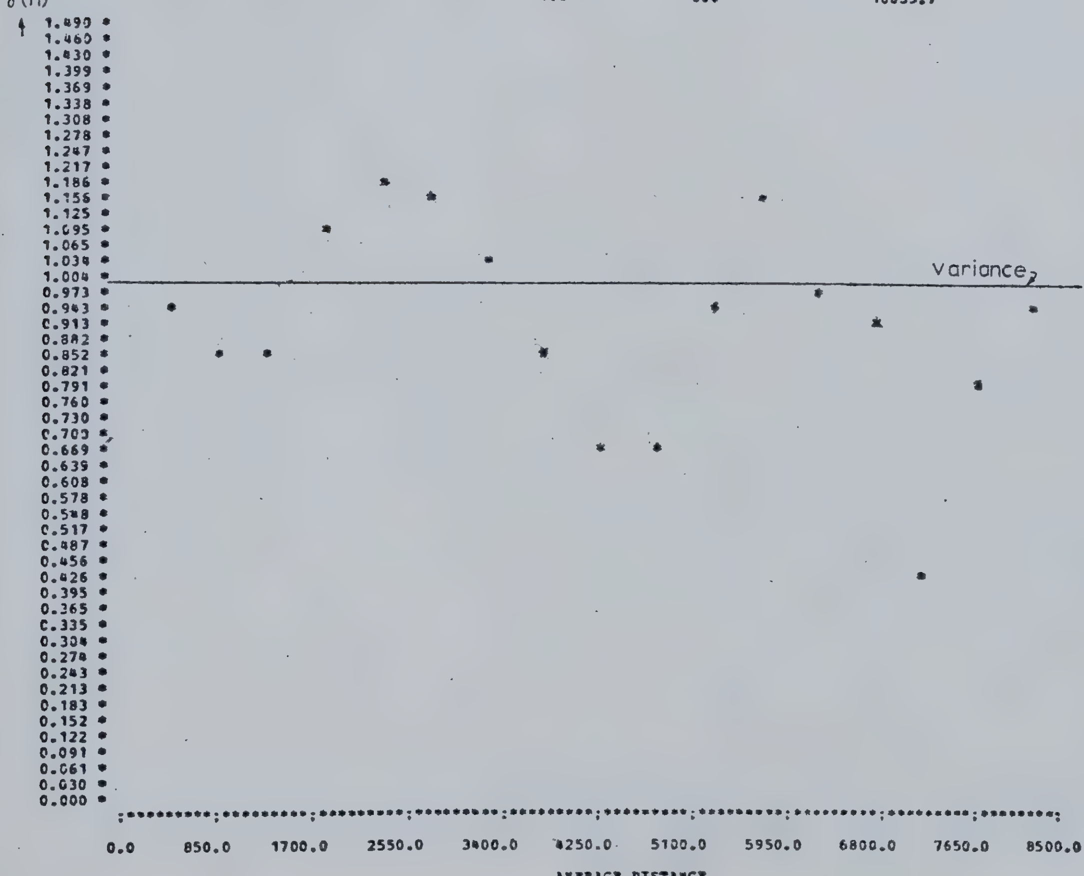


Fig 8,7 VARIOGRAM with direction = 60° or 240°

VARIOGRAM WITH A FIELD OF 90. DEGREES IN EACH DIRECTION.

STEP IN METERS = 500.0000

UPPER LIMIT FOR Z = 30.0000

GENERAL MEAN OF Z = 3.9208

GENERAL VARIANCE OF Z = 0.9937

DISTANCE IN METERS	NB. OF PAIRS	DRIFT	VARIOGRAM	AVERAGE DISTANCE
0 ---- 500	75	-0.213	0.8667	367.5
500 ---- 1000	176	-0.057	1.0341	766.9
1000 ---- 1500	202	-0.005	1.0965	1254.5
1500 ---- 2000	200	-0.095	1.0675	1757.0
2000 ---- 2500	219	-0.274	1.2968	2243.7
2500 ---- 3000	207	0.188	1.1232	2735.1
3000 ---- 3500	213	-0.047	0.9906	3239.2
3500 ---- 4000	215	0.028	0.8419	3740.9
4000 ---- 4500	200	-0.160	0.7400	4262.8
4500 ---- 5000	164	0.122	0.8049	4740.3
5000 ---- 5500	128	-0.055	1.0430	5218.9
5500 ---- 6000	87	0.264	1.4195	5707.6
6000 ---- 6500	36	0.000	1.1389	6195.7
6500 ---- 7000	21	-0.333	1.0714	6731.1
7000 ---- 7500	7	1.143	1.2857	7141.9

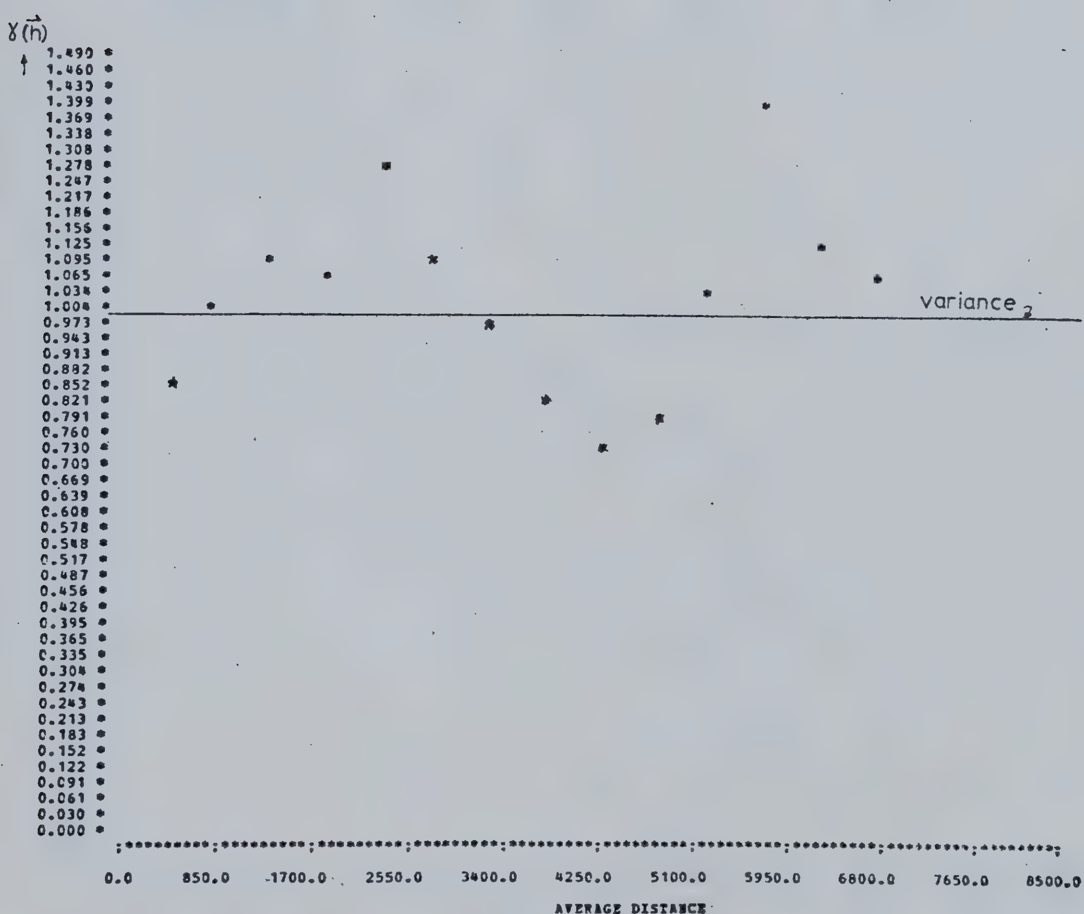


Fig 8.8 VARIOGRAM with direction = 90° - 270°

VARIOGRAM WITH A FIELD OF 90. DEGREES IN EACH DIRECTION

STEP IN METERS = 500.0000

UPPER LIMIT FOR Z = 30.0000

GENERAL MEAN OF Z = 3.9208

GENERAL VARIANCE OF Z = 0.9937

DISTANCE IN METERS	NB. OF PAIRS	DRIFT	VARIOGRAM	AVERAGE DISTANCE
0 ---- 500	74	-0.176	0.8716	369.6
500 ---- 1000	176	-0.068	0.9829	763.1
1000 ---- 1500	195	-0.041	0.9949	1251.1
1500 ---- 2000	204	-0.127	0.8774	1751.9
2000 ---- 2500	186	-0.301	1.2150	2251.3
2500 ---- 3000	150	0.233	0.9500	2739.8
3000 ---- 3500	158	-0.013	0.8354	3249.2
3500 ---- 4000	145	-0.055	0.9724	3744.7
4000 ---- 4500	129	-0.163	1.0969	4265.4
4500 ---- 5000	117	-0.137	1.0427	4754.9
5000 ---- 5500	111	-0.027	1.1847	5241.6
5500 ---- 6000	107	0.150	1.2149	5724.9
6000 ---- 6500	84	0.024	1.4286	6238.1
6500 ---- 7000	85	0.271	1.5235	6739.3
7000 ---- 7500	77	0.000	1.3766	7237.6
7500 ---- 8000	50	0.180	1.4700	7741.6
8000 ---- 8500	31	0.677	1.8871	8202.2
8500 ---- 9000	9	0.222	1.2222	8665.3
9000 ---- 9500	1	1.000	0.5000	9110.6

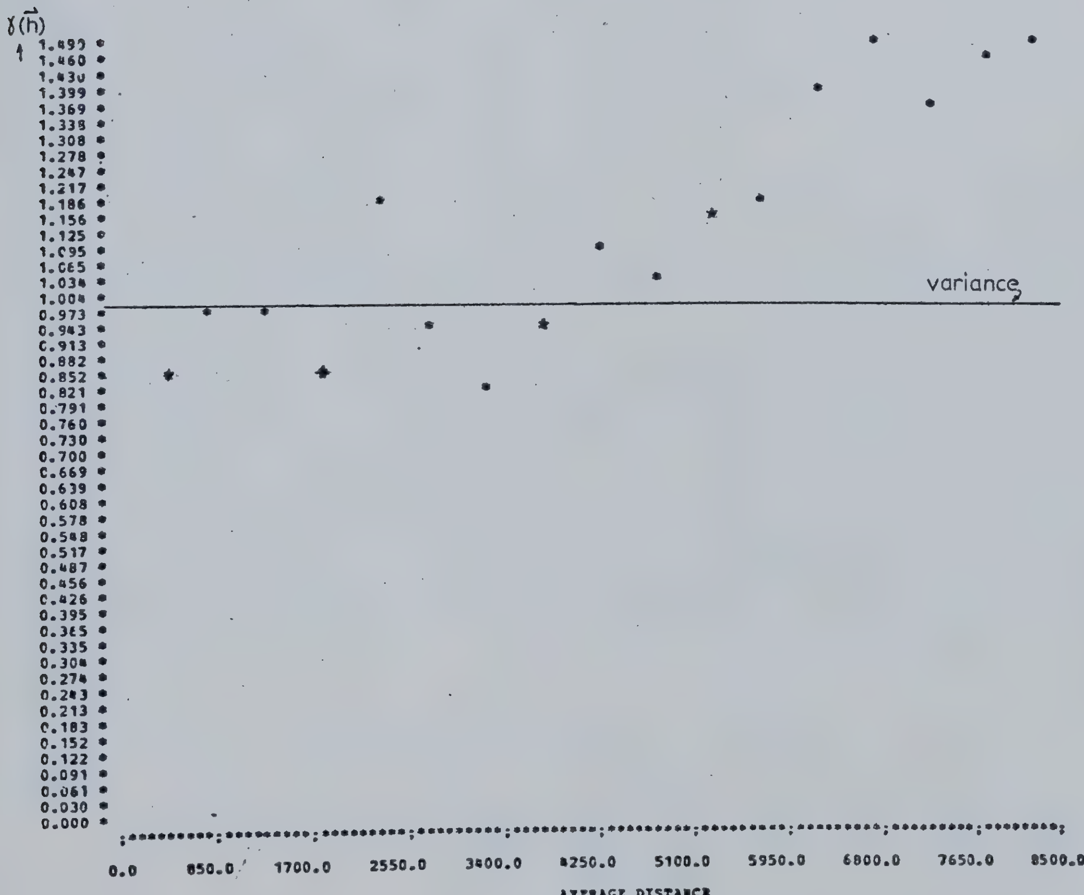


Fig 8.9 VARIOGRAM with direction = 120° or 300°

VARIOGRAM WITH A FIELD OF 90. DEGREES IN EACH DIRECTION

STEP IN METERS = 500.0000

UPPER LIMIT FOR Z = 30.0000

GENERAL MEAN OF Z = 3.9208

GENERAL VARIANCE OF Z = 0.9937

DISTANCE IN METERS	NB. OF PAIRS	DRIFT	VARIOGRAM	AVERAGE DISTANCE
0 ---- 500	73	-0.096	0.6507	366.7
500 ---- 1000	170	-0.153	0.9294	758.6
1000 ---- 1500	210	-0.057	0.8952	1252.7
1500 ---- 2000	239	-0.172	0.6004	1748.3
2000 ---- 2500	203	-0.197	0.9458	2267.2
2500 ---- 3000	176	0.119	0.6903	2761.9
3000 ---- 3500	157	-0.006	0.8121	3243.9
3500 ---- 4000	140	-0.079	0.7968	3735.6
4000 ---- 4500	135	-0.133	1.0370	4253.7
4500 ---- 5000	123	0.171	1.0293	4742.0
5000 ---- 5500	131	0.183	1.2214	5252.9
5500 ---- 6000	127	0.134	1.2165	5727.7
6000 ---- 6500	150	0.327	1.3766	6248.8
6500 ---- 7000	151	0.397	1.5496	6727.8
7000 ---- 7500	164	-0.012	1.1646	7238.1
7500 ---- 8000	105	0.324	1.4571	7740.3
8000 ---- 8500	63	0.524	1.7063	8208.6
8500 ---- 9000	24	0.250	0.9583	8678.5
9000 ---- 9500	3	1.000	0.8333	9124.1

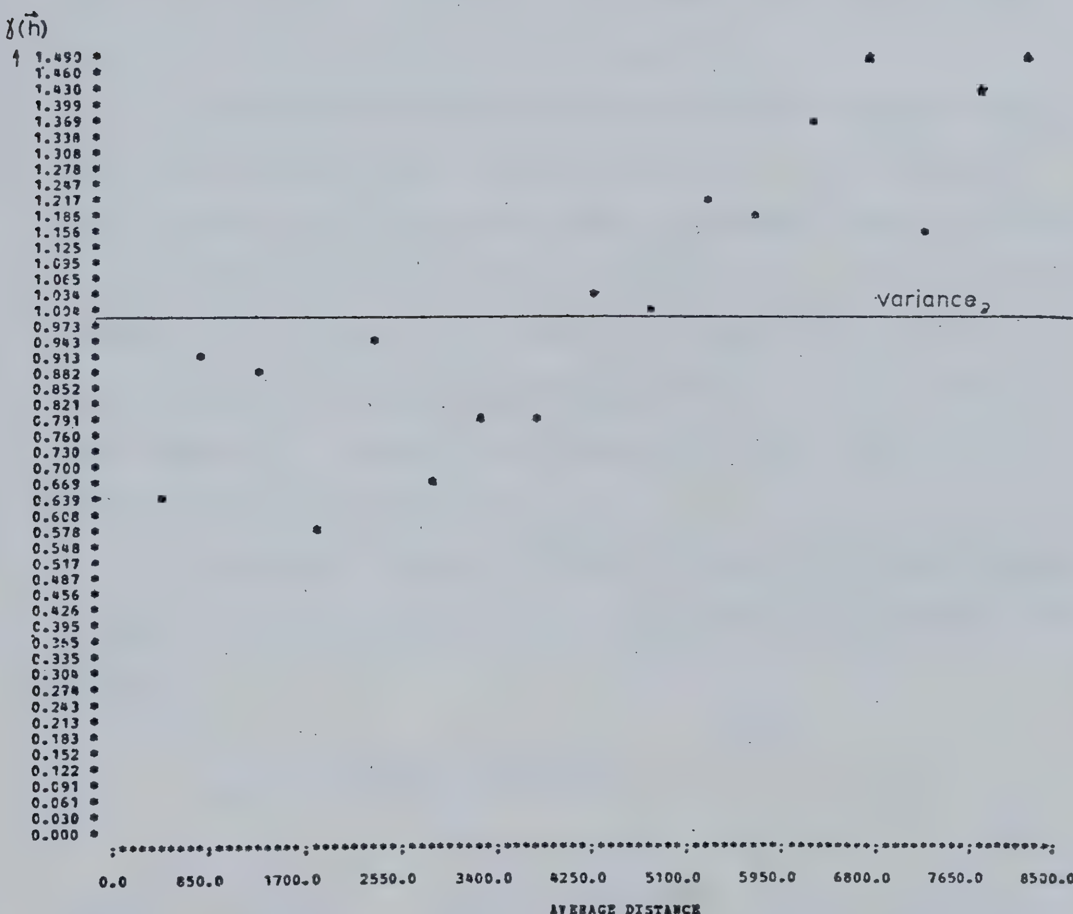


Fig 8.10 VARIOGRAM with direction = 150°~330°

gram study because the area has very good well denisty and the seam is relatively widespread, some of the wells have a complete suite of logs and most of the boreholes penetrate the seam. More data are available than for any other seam in any other area.

B. RESULTS AND INTERPRETATION OF THE VARIOGRAMS

In statistics, the variance of a variable (e.g., seam thickness) is a measure of how the variable is spread out around the mean. The more commonly used value is the standard deviation which is the square root of the variance. In this variogram study, three kinds of variance (figure 8.11) are involved and are discussed below.

1. Variance of sampling error is represented by the nugget effect (Co) in the variogram curve (David, 1974, p. 62). In this study, all the variograms show a high nugget effect value meaning that in determining the seam thickness from the geophysical logs used, an error was introduced by the sampler. This error arises because the resolution of the logs used is about two feet and the thickness was read to the nearest foot. With better log resolution, the accuracy could improve, hence decreasing the nugget effect.

2. Variance due to natural random variation of the seam thickness is here called sample variance. This variance can be calculated by the formula:

$$\delta^2 = \frac{\Sigma(n \times th)^2 - (\Sigma\ n \times th)^2}{N}$$

where δ^2 = variance, n = number of observations that have thickness th, th = thickness of seam, and N = total number of observations.

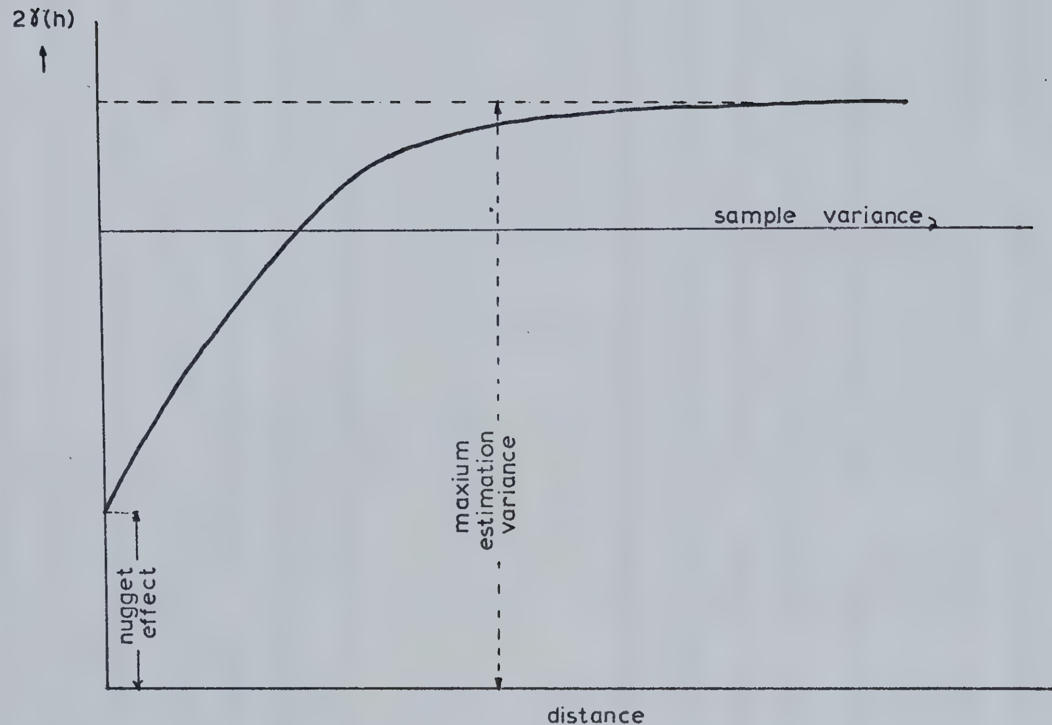


Fig 8.11 TYPES of VARIANCE ASSOCIATED with the VARIOGRAM

In this study, the sample variance is 0.9937 feet^2. However, this sample variance is directly affected by the sampling error. If an error is introduced during determination of seam thickness, the sample variance calculated becomes an unreliable estimation of the natural random variation of the seam thickness. In view of the high nugget effect value (approximately 0.7 to 0.8 ft^2) obtained in this study, 0.9937 feet^2 is probably not representative of the true value of the sample variance.

3. The third type of variance is that of the error made when estimating, say, seam thickness at point (x+h) using the thickness at point x, which is h units from the former point. This variance is known as estimation variance. Huijbregts (1975, p. 41) has shown that the variogram being the average quadratic difference between thickness at (x+h) and thickness at x, i.e.,

$$2\gamma(\vec{h}) = \text{average } [th_{(x)} - th_{(x+h)}]^2$$

this function is an estimation variance. The estimation variance in all types of variograms (figure 8.1), except the random type, increases as the distance between the pair of points increases. It means that in extrapolating a data value, the farther away from the control point, the higher is the variance introduced into the estimated value. The maximum of the estimation variance is represented by the sill of the curve. Along the sill, the estimation variance is independent of the distance between the point-pair. The zone of influence is defined as the distance at which the variogram curve reaches a plateau (the sill), i.e., where the estimation variance reaches the maximum.

If the estimation variance at distance h is less than or equal to the sample variance, then the estimated thickness at point (x+h) using the thickness at point x is statistically reliable. Furthermore, the zone of influence determined from the variogram is also reliable. On the other hand, if the estimation variance is greater than the sample variance, the estimated thickness at point (x+h) and zone of influence are unreliable. The following example will illustrate the situation.

Suppose at point x, a borehole encounters a 5-foot thick seam. The geologist would like to know what is the thickness of this seam at, say, one mile away. From the data on the same seam in the area, he has calculated the sample variance as 1 foot^2 (standard deviation = 1 ft). From the variogram, he obtains an estimation variance of 4 feet^2 (standard deviation = 2 ft) at a distance of one mile. Assuming there is no sampling error, then the information from the variogram indicates that the seam thickness at a point one mile away from the borehole will be (5±2) feet. However, the actual range of the seam thickness at that point should be (5±1) feet as indicated by the sample variance. That means the variogram cannot be used to extrapolate seam thickness from one point to another with a distance of one mile in between.

In the present study, the semi-variogram, $\gamma(\vec{h})$, shows a large nugget effect and crosses over the sample variance as the distance increases. As has already been discussed, the high nugget effect value decreases the reliability of the sample variance. Because of this unreliability, it is not possible to compare the sample variance with the estimation variance with any degree of certainty. Without this comparison, the zone (or range) of influence cannot be determined with confidence. Furthermore,

there is a possibility that the control point spacing in this study is not close enough to provide information on the initial portion of the variogram curve near the origin. It is this initial portion of the variogram that gives the vital evidence on the continuity of the deposit. Moreover, without geophysical logs of better resolution, the error introduced in the estimation of coal seam thickness rendered the statistics used in this variogram study unreliable. Therefore, closer well spacing as well as better log resolution are needed in order to determined whether the variogram can be used to predict palaeodrainage direction.

Chapter 9

SUMMARY AND CONCLUSIONS

The facies change from the distinct six-member Mannville Formation as defined by Nauss (1945) to the Undifferentiated Mannville Group (Maycock, 1967) occurs in the vicinity of Township 40 in west-central Saskatchewan, and is attributed to the presence of the Battleford Arch. The circumstantial evidence for this is the pinching out of both the Dina and Cummings Members in that general vicinity and the absence of coal seam 8 in Townships 37 to 39. The arch was high either during or after the deposition of seam 8 depending on whether the absence of the seam in Townships 37 to 39 was due to non-deposition or erosion. Since no unconformity was detected on top of this seam, the absence of seam 8 in this area was probably due to non-deposition.

The Battleford Arch also had a subtle effect on the depositional environments of the Mannville Group. North of the arch, depositional environments changed from fluvial during Dina time to nearshore and/or deltaic in the later part of the Mannville history. On the other hand, south of the Battleford Arch, Mannville sediments are mainly of continental origin as indicated by the lack of marine fossils and the abundance of coal seams.

Coal seams in the Mannville Group are scattered both geographically and stratigraphically as shown by their distribution maps, centre of gravity map and relative standard deviation map. Deposition of coal was confined mainly to the palaeotopographic lows during Mannville time (figures 8.1 and 6.4) with the loci of deposition migrating frequently, producing thin coal seams scattered vertically through the Mannville beds.

A total of ten seams were identified from geophysical borehole logs with only seams 3 and 8 having relative regional significance. Distribution of the minor seams can be explained by Price and Ball's (1971) model which postulates that the coal was of drift origin, perhaps forming from log jams on the river banks rather than originating in widespread swampy areas. The two major seams, 3 and 8, may have been deposited in swamps on the fluvial plain, giving them larger areal distributions. The fact that seam 8 occurs both in the northern and southern portions of the study area makes it a useful stratigraphic marker for correlation within the Mannville Group.

Coal resources in place calculated on a one-well-per-township basis were estimated to be 19,400 million (short) tons, including seams 2 feet thick or thicker. Using seam thickness as the variable, a variogram study was carried out in part of the area. Due to the lack of a reliable estimation of the sample variance for seam thickness, it was not possible to determine the zone (or range) of influence of a data point. With the knowledge of the zone of influence and the depositional environments of the study area, the variogram may be a useful tool to predict palaeodrainage direction.

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